νPRISM: An Experimental Method to Remove Neutrino Interaction Uncertainties from Oscillation Experiments

Mike Wilking, Stony Brook University
Workshop on the Intermediate Neutrino Program
February 5th, 2015

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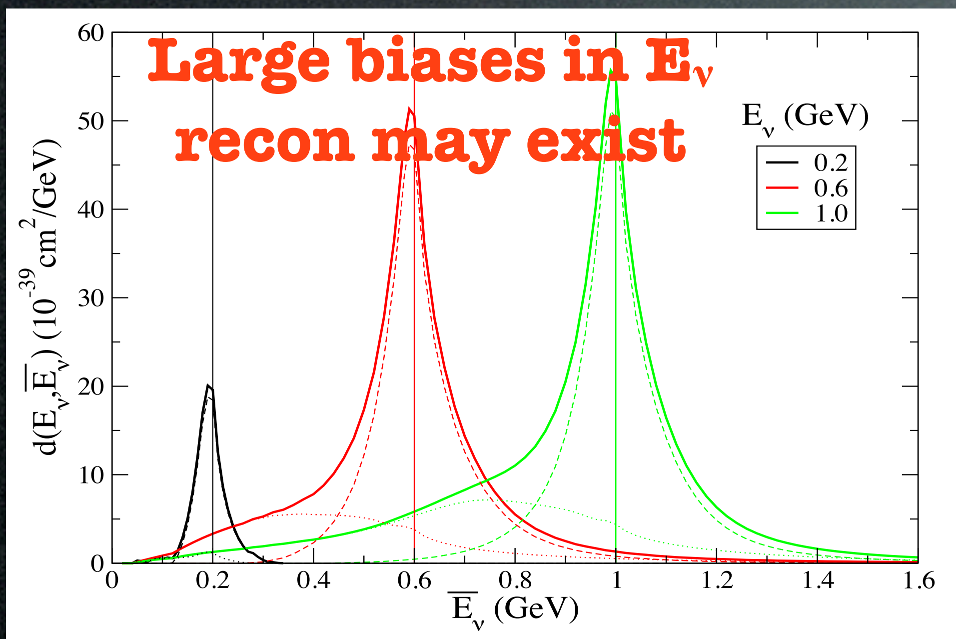
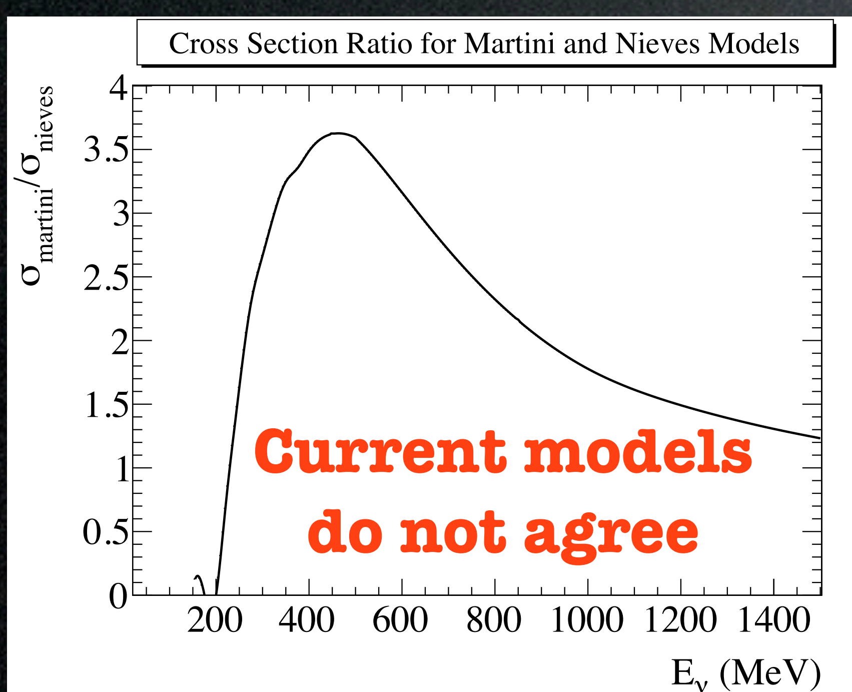
Why LB-ν Needs NuPRISM:

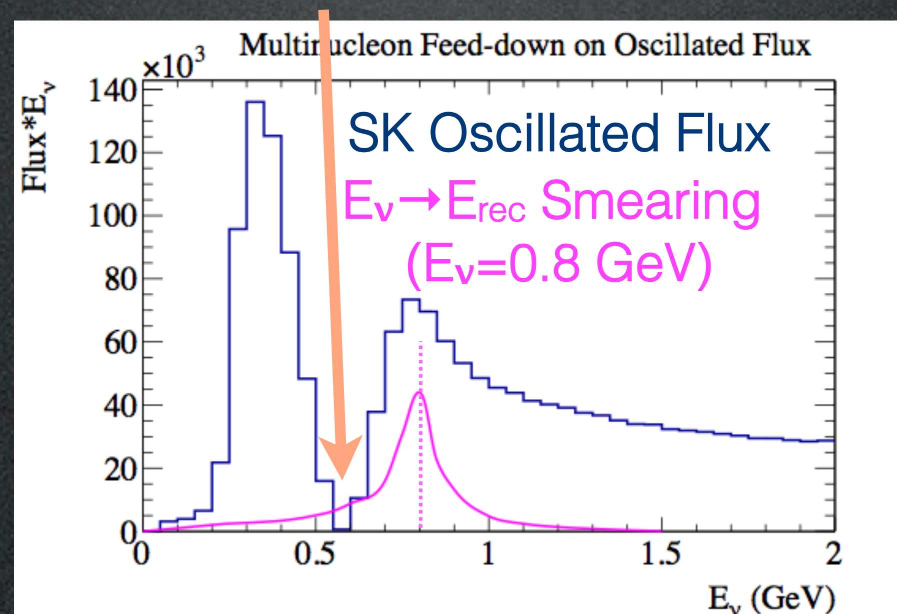
The E_ν Measurement Problem



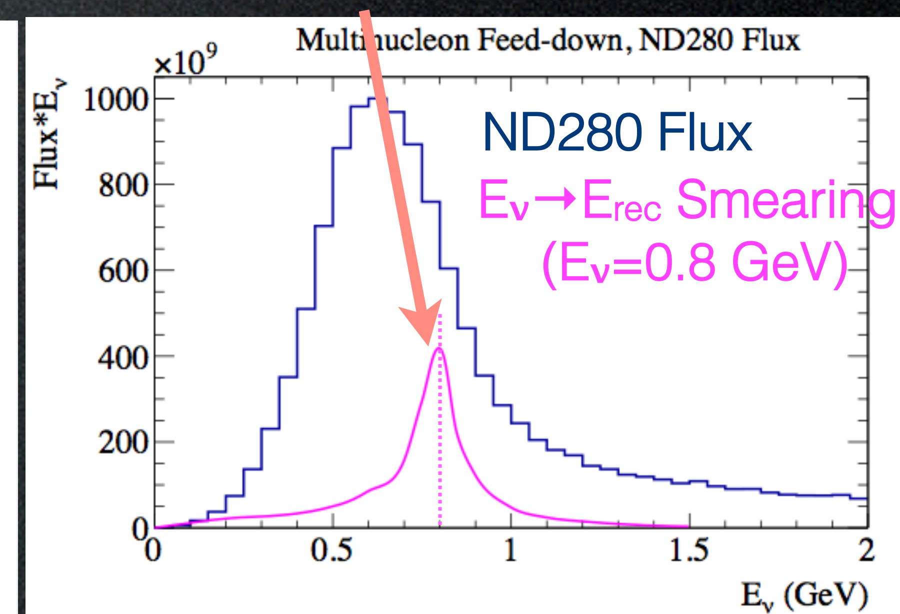
- It is now believed that large E biases can exists due to nuclear and non-nuclear effects (e.g. multinucleon interactions)
- Models are very difficult to produce and show large disagreements
- Without a data-driven constraint, this will likely be a dominant uncertainty for T2HK
- Typical near detectors likely cannot provide a sufficient constraint



Mixing Angle Bias!



Typical ND lacks sensitivity



- J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, PRC 83:045501 (2011)
- M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PRC 80:065501 (2009)

Reminder: NuPRISM Detector Concept

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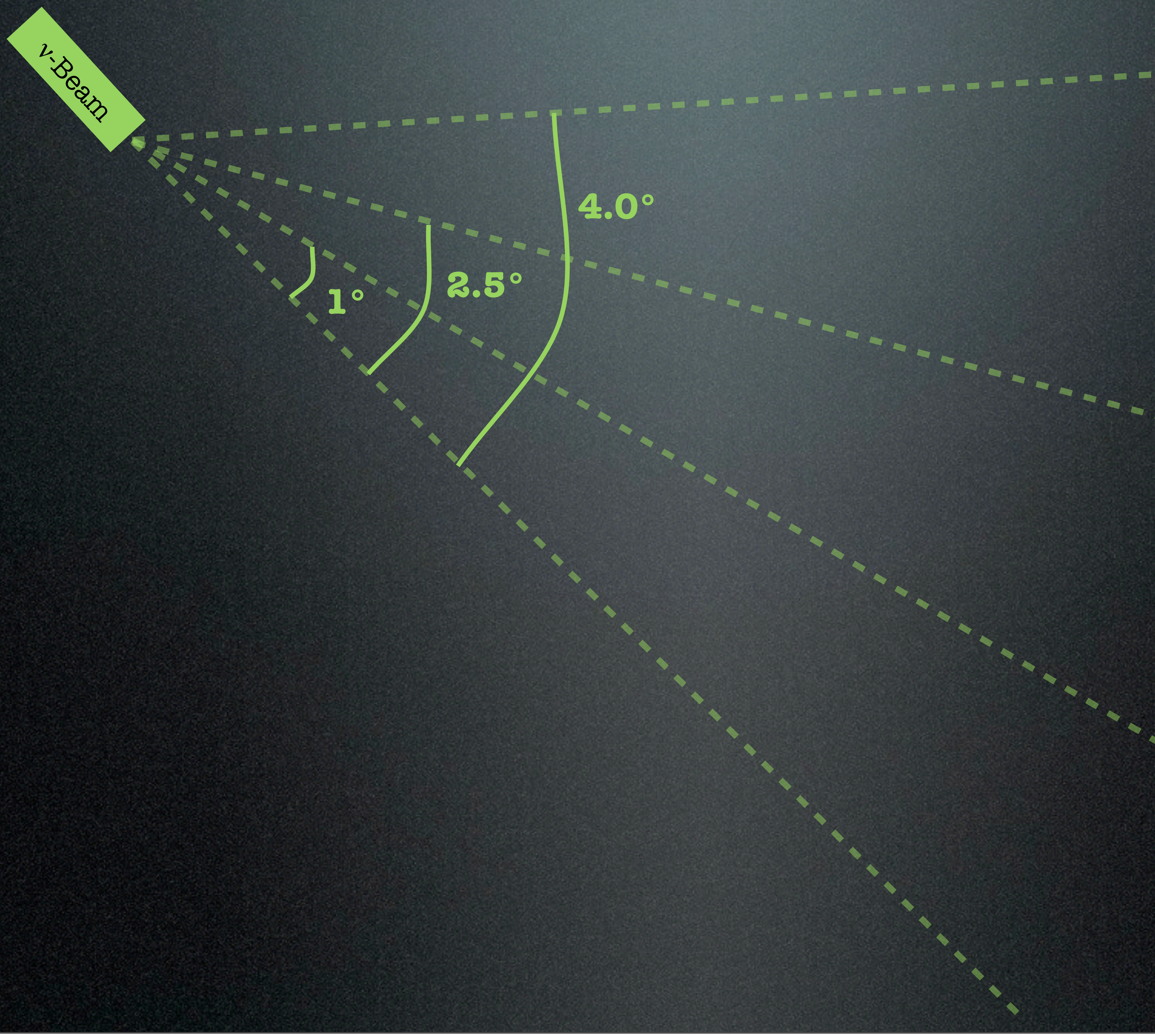
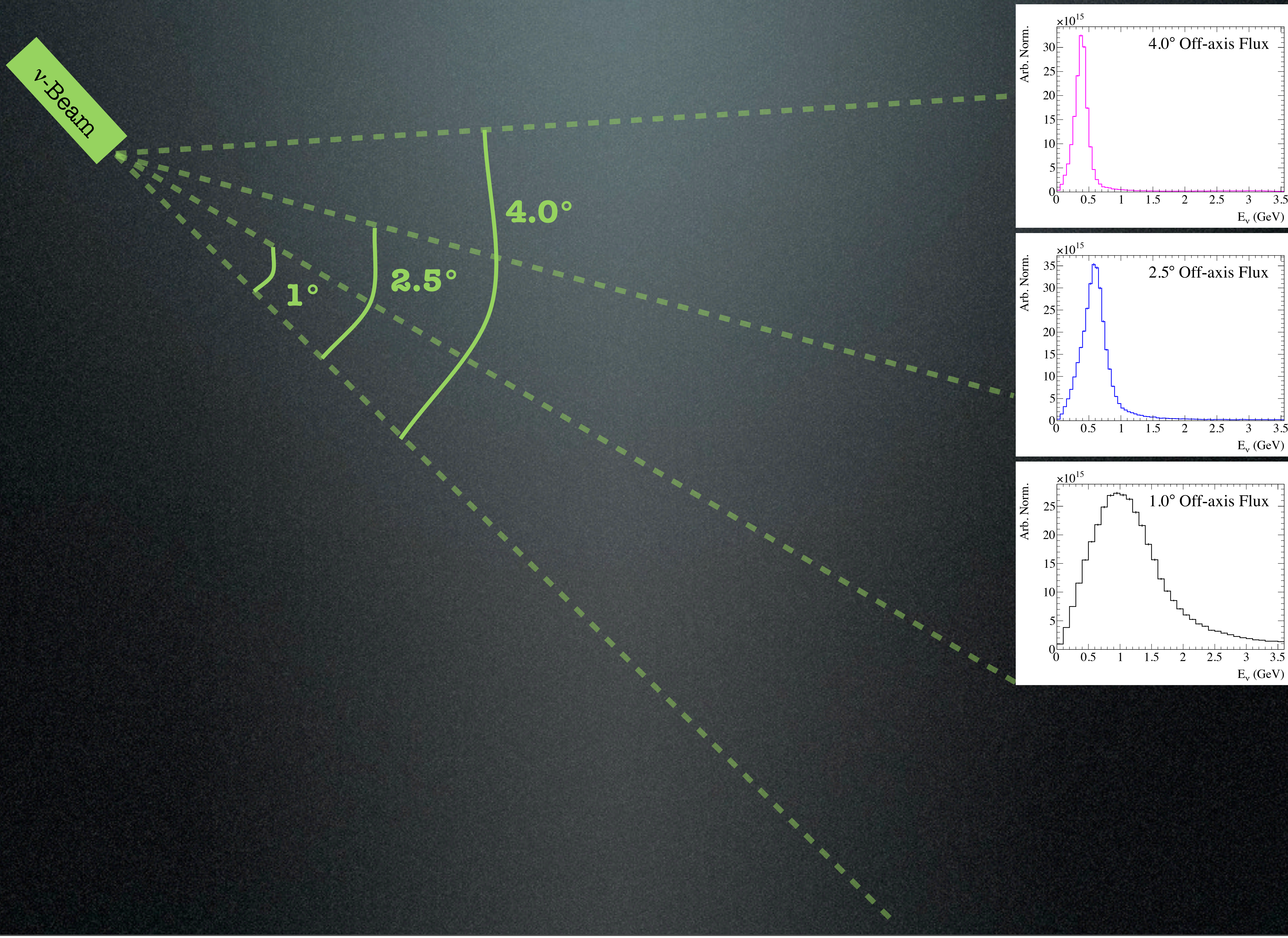


Reminder: NuPRISM Detector Concept



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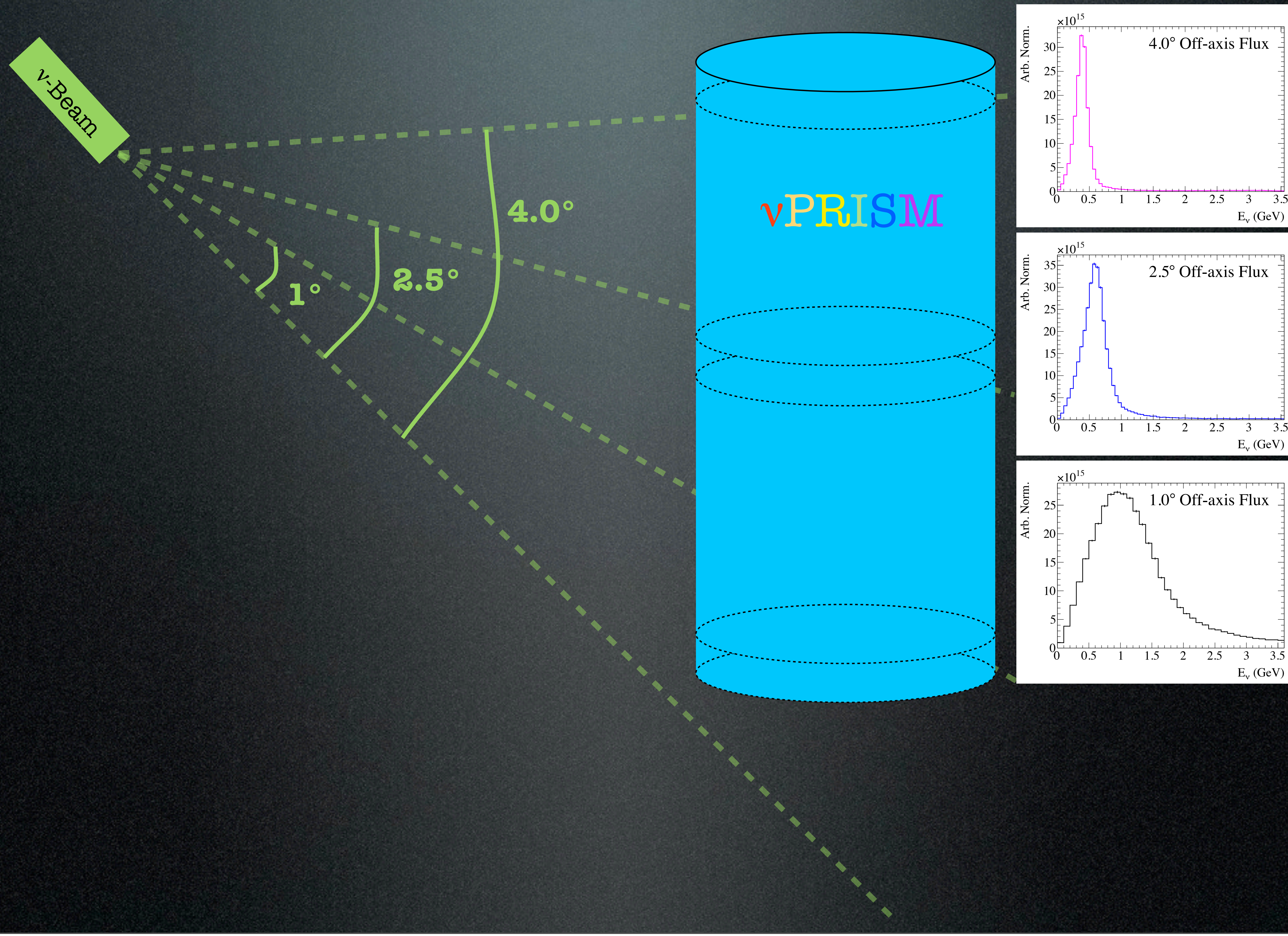

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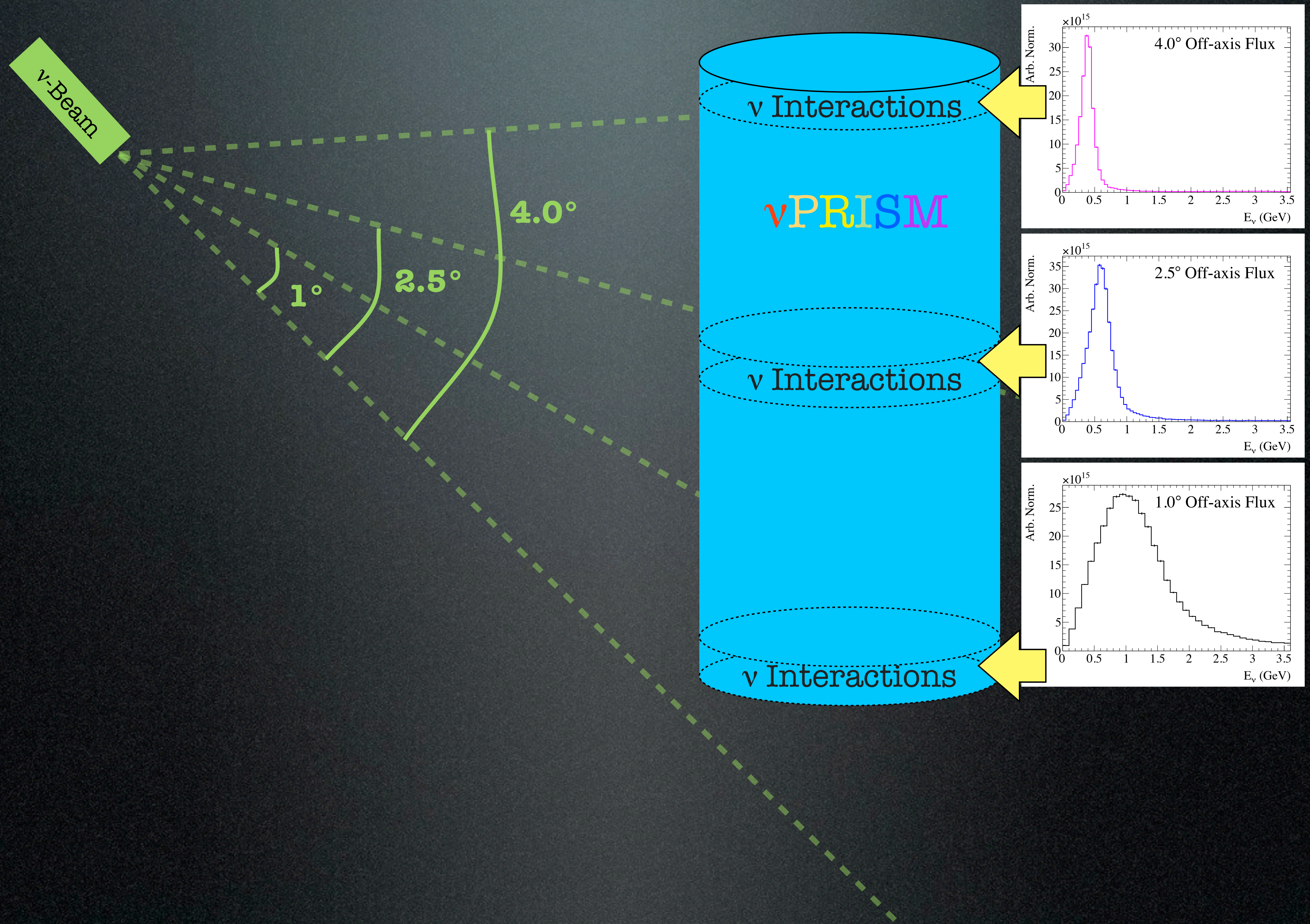

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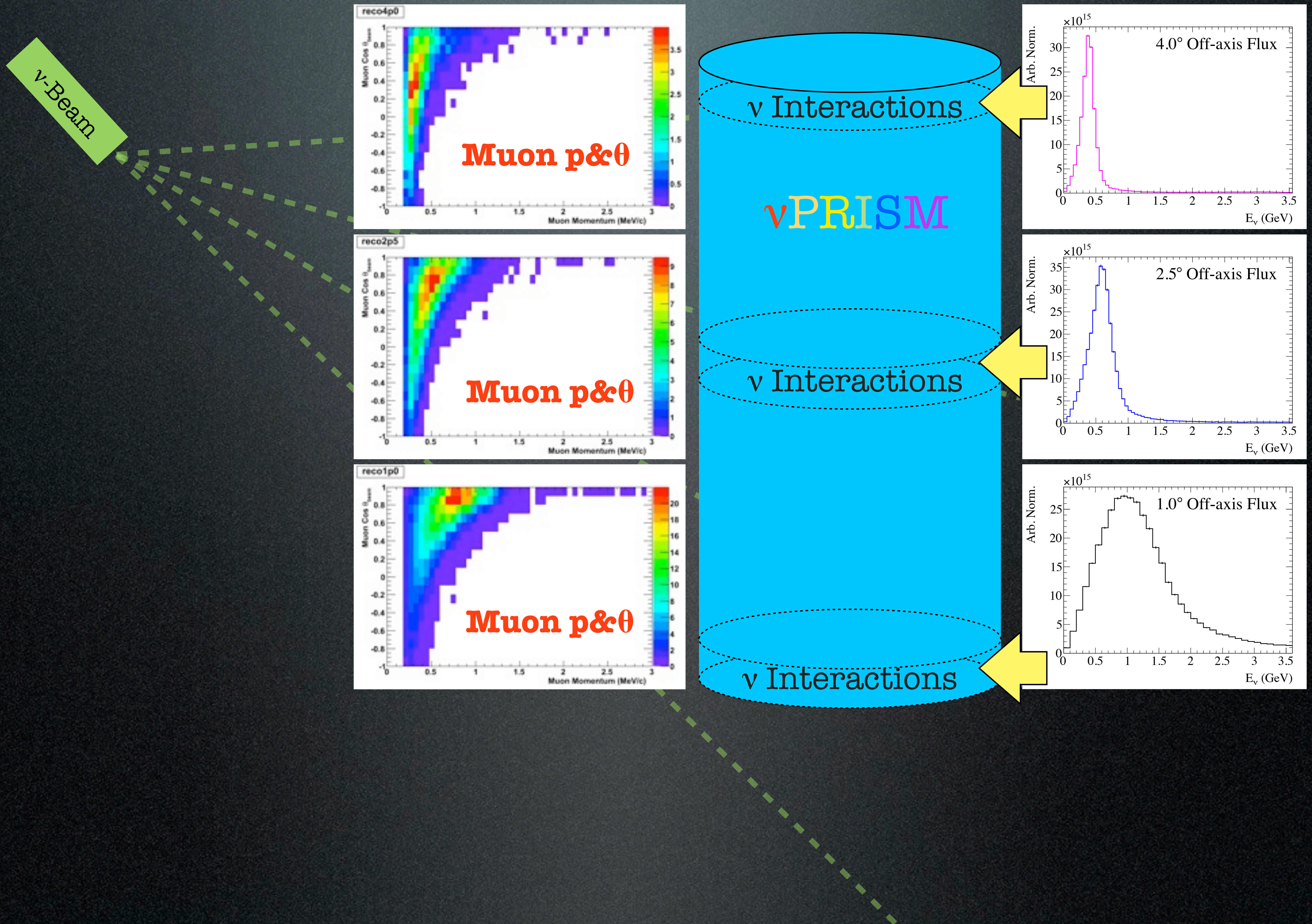

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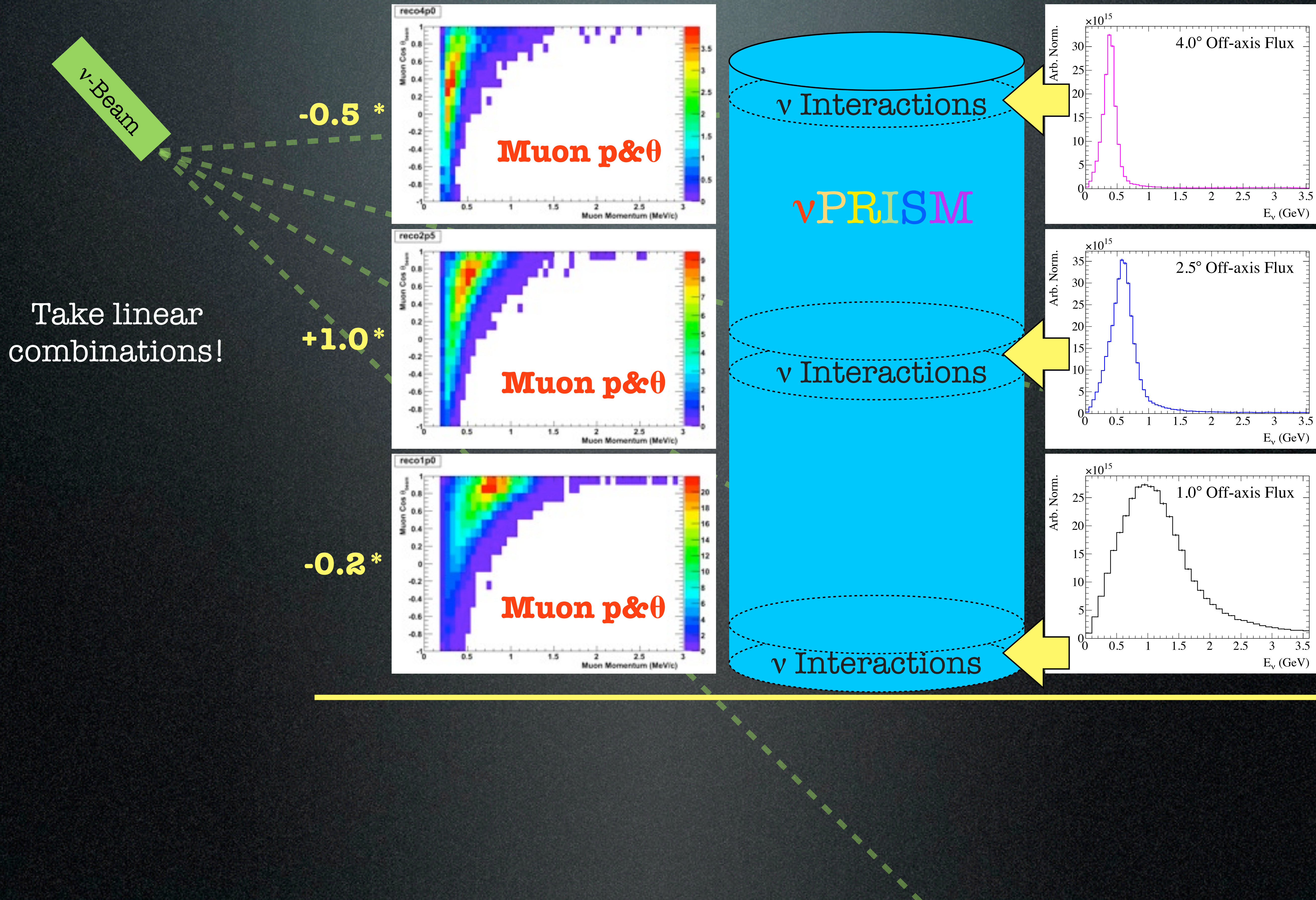

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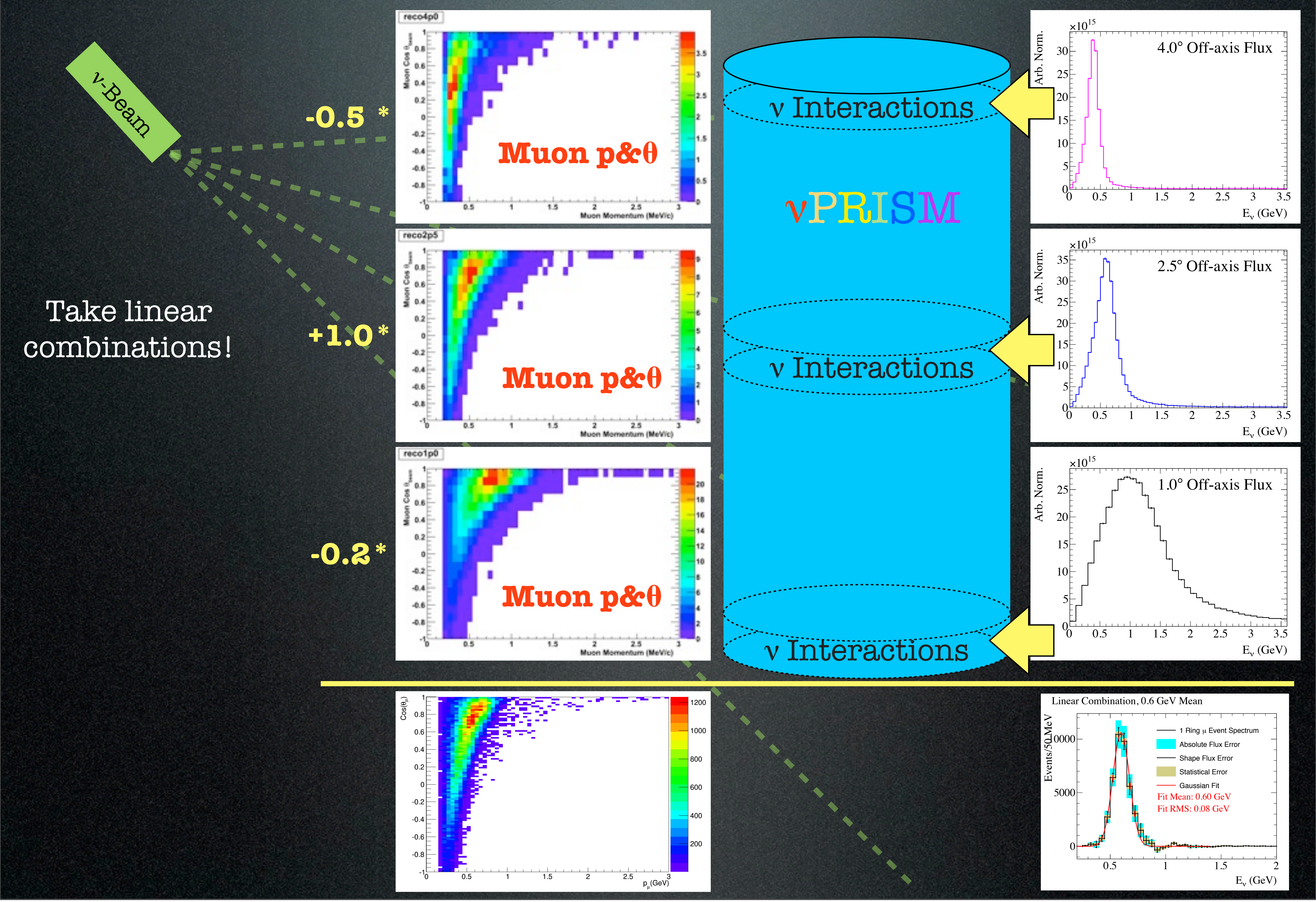
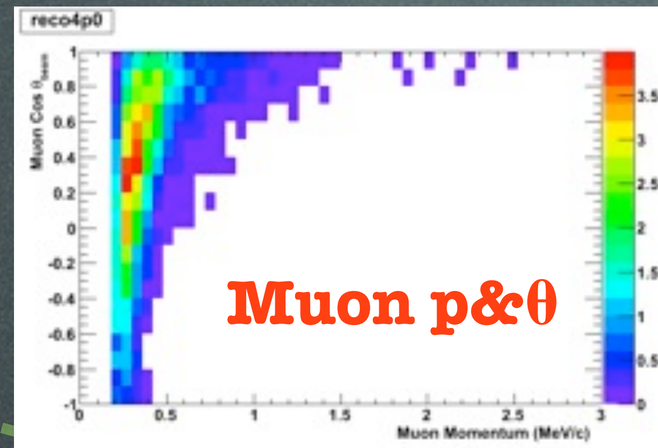
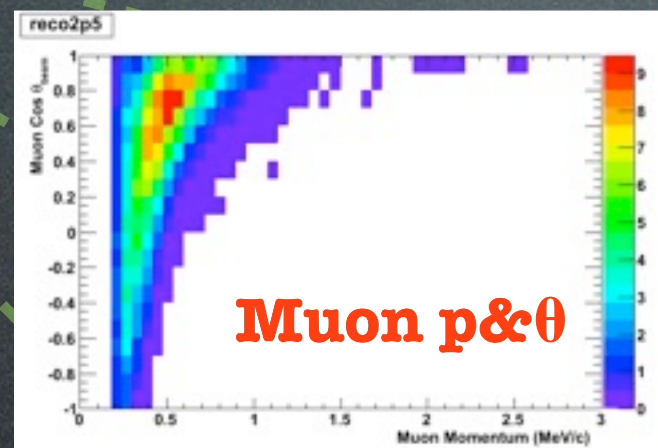


Reminder: NuPRISM Detector Concept

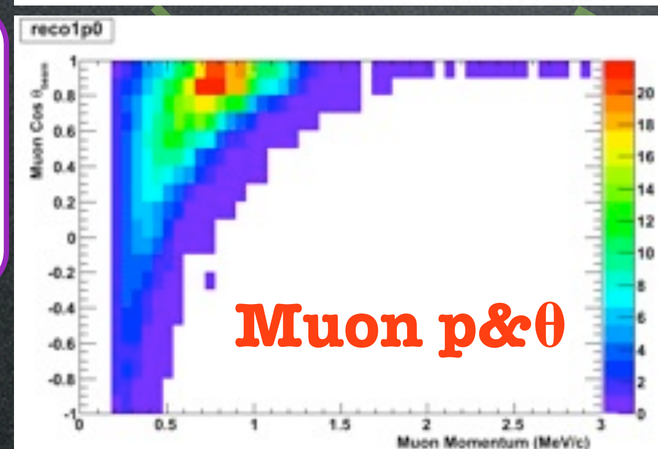
ν-Beam

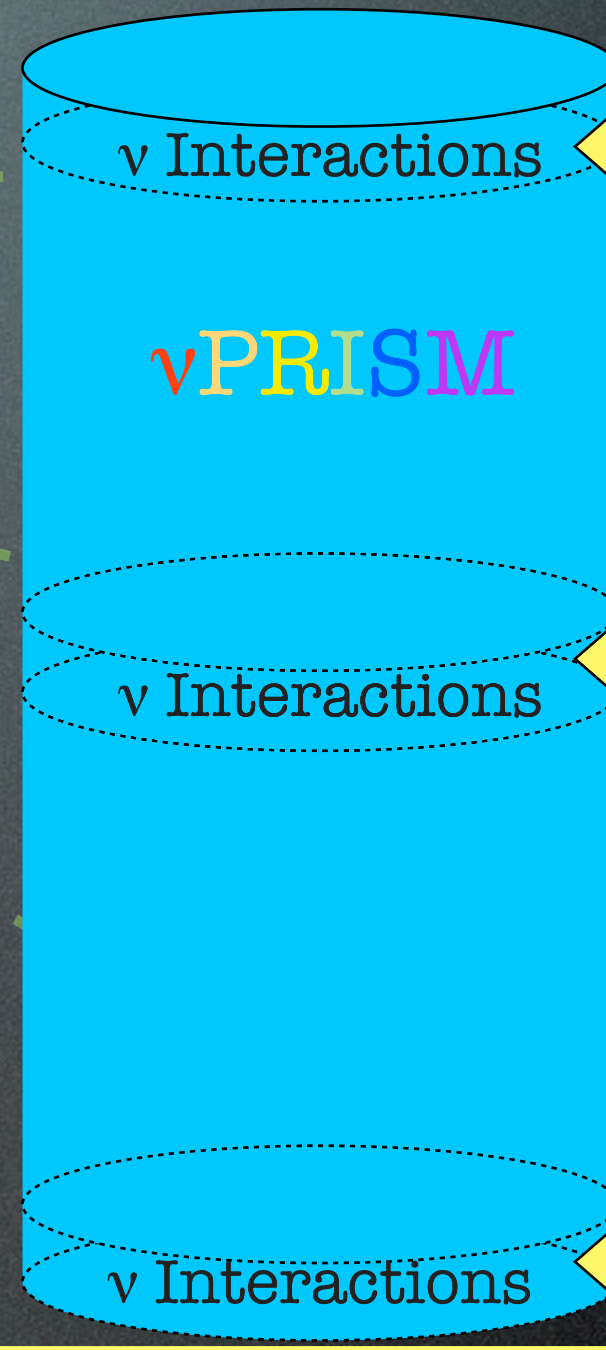
-0.5 *

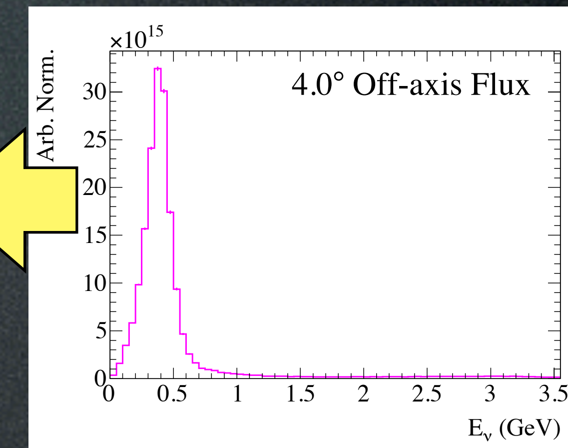


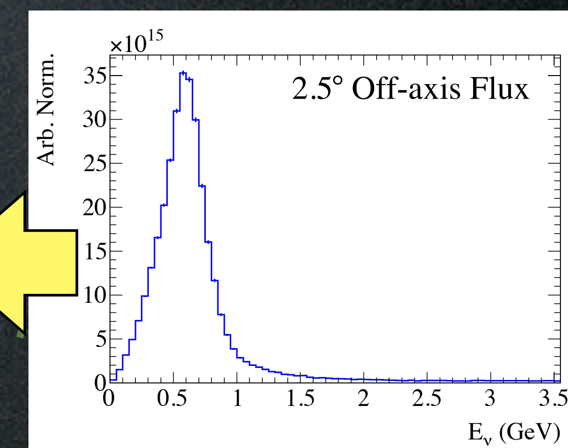


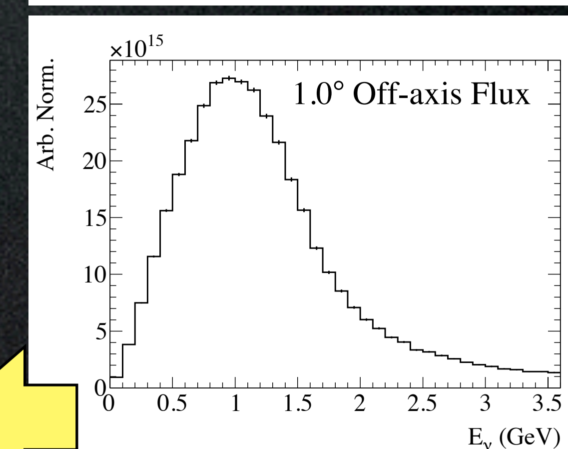
+1.0 *





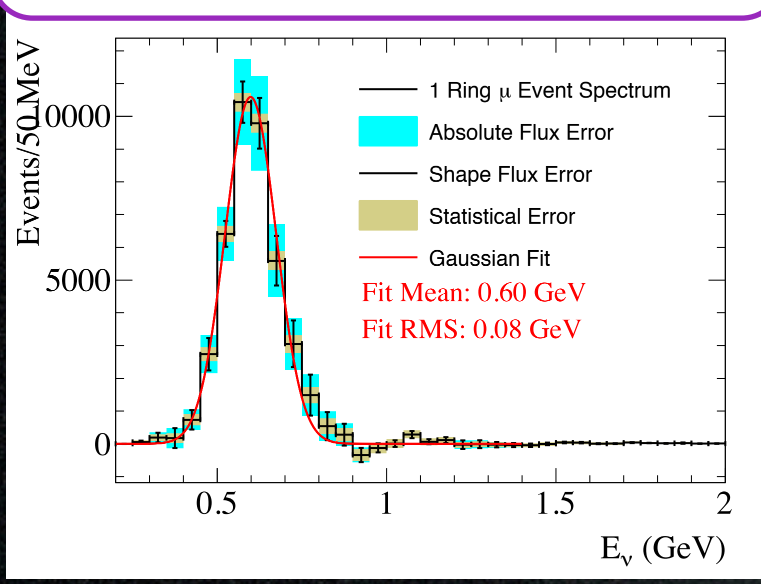


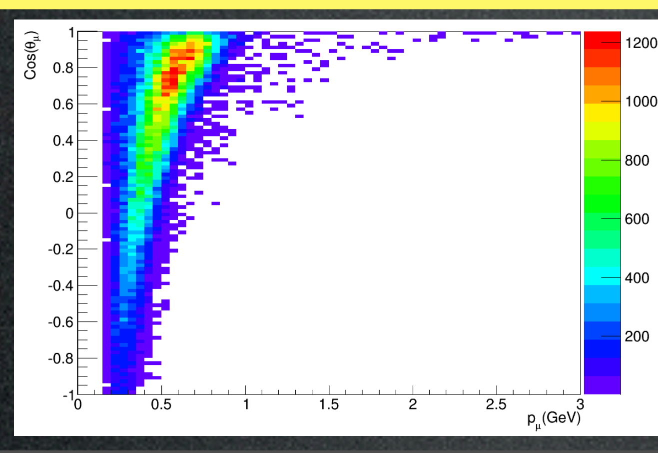


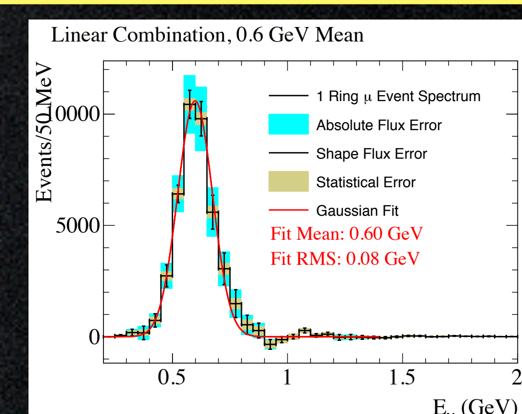


Take linear combinations!

600 MeV Monoenergetic Beam using 60 slices in off-axis angle

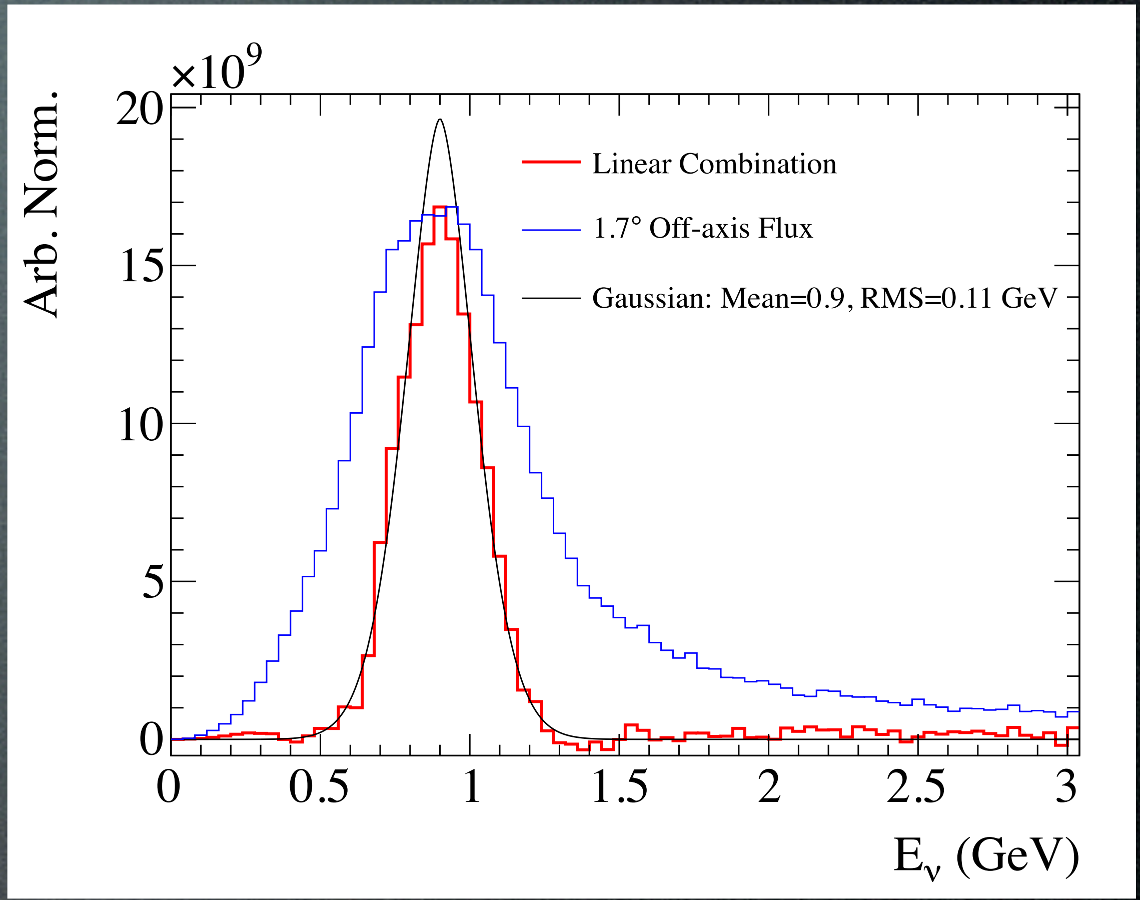


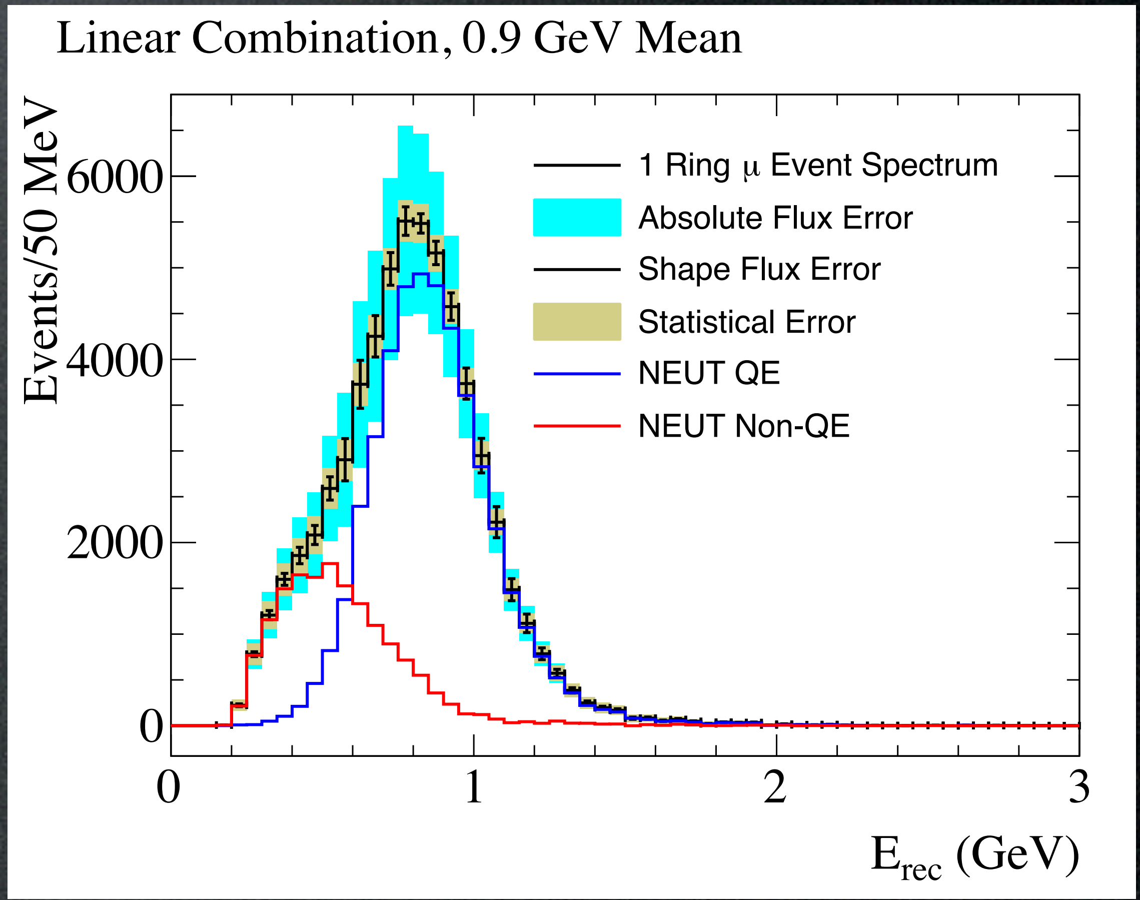




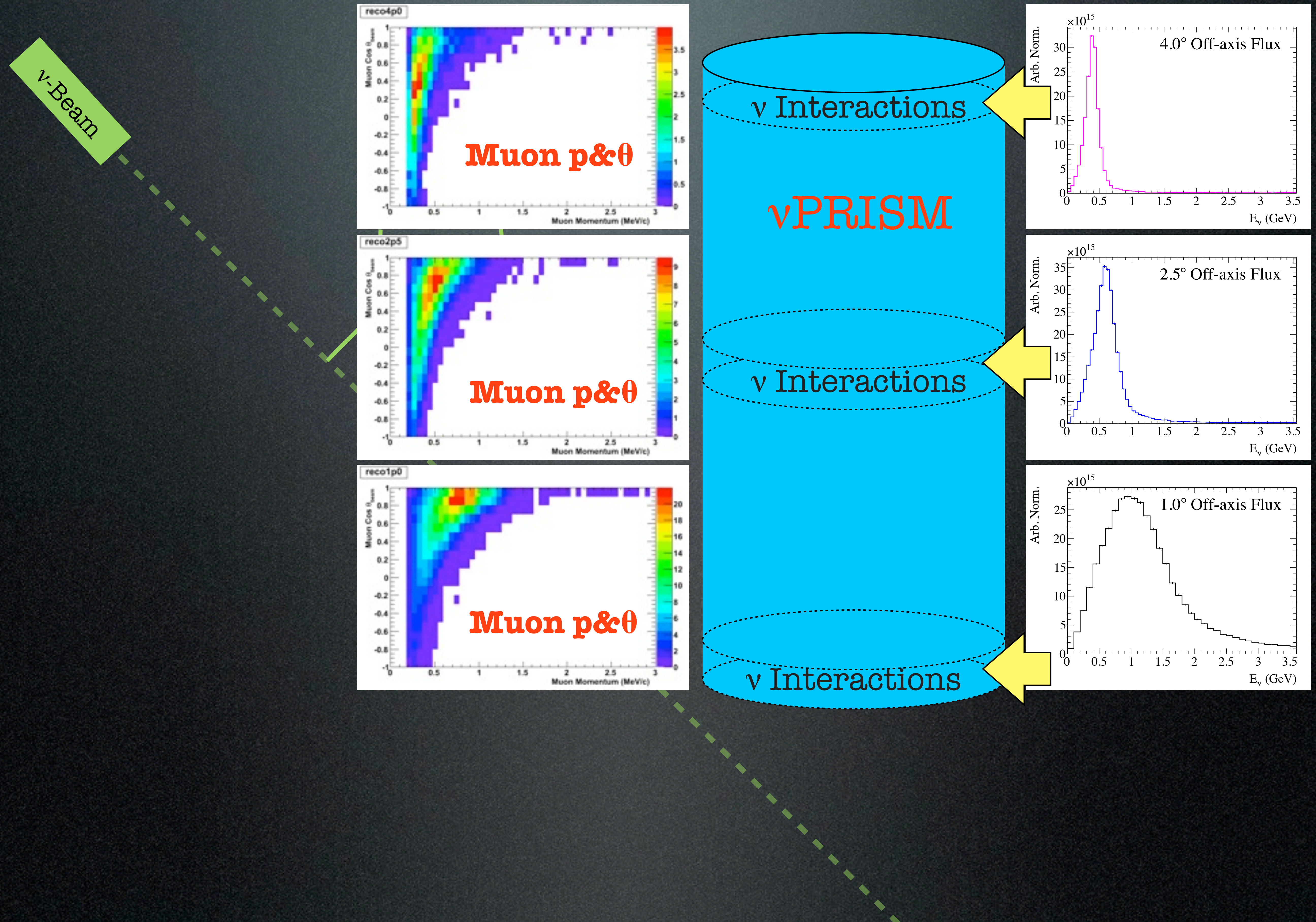
Benefits of a Monoenergetic Beam

- First ever measurements of NC events with E_ν
  - Much better constraints on NC oscillation backgrounds
- First ever "correct" measurements of CC events with E_ν
  - No longer rely on final state particles to determine E_ν
- It is now possible to separate the various components of single-μ events!
- This is also very interesting to the nuclear physics community



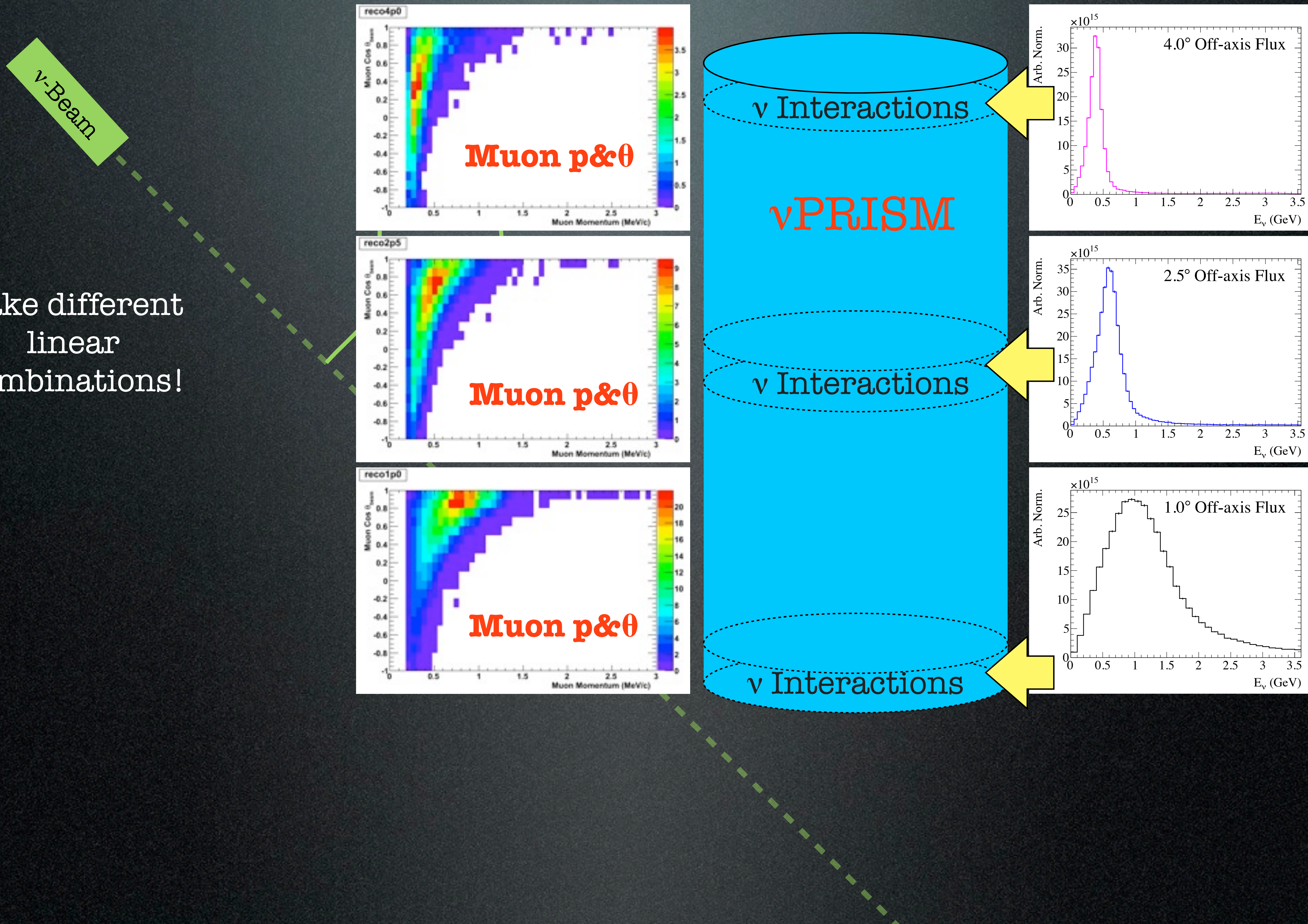


NuPRISM in Oscillation Analyses



NuPRISM in Oscillation Analyses

Take different linear combinations!



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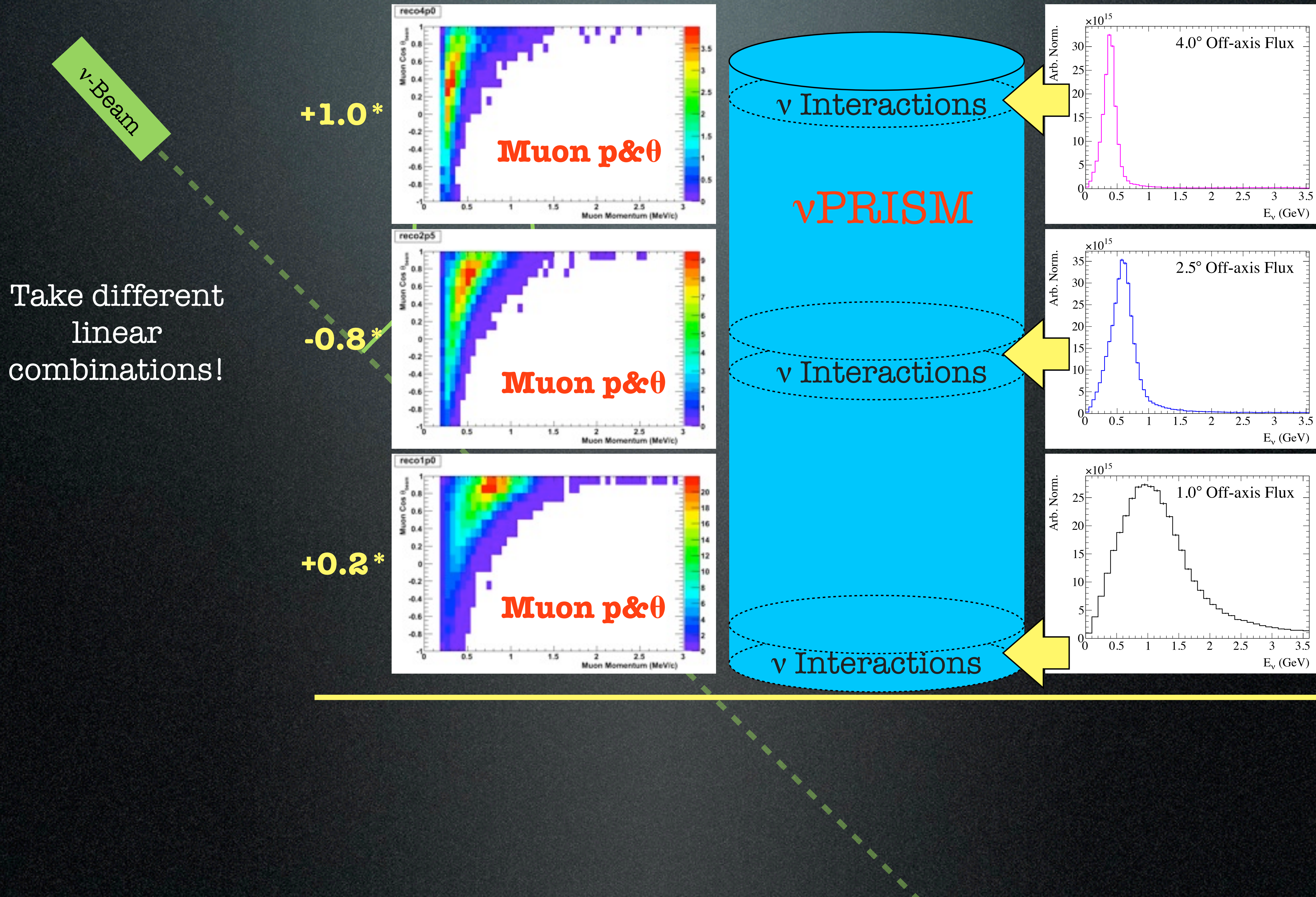
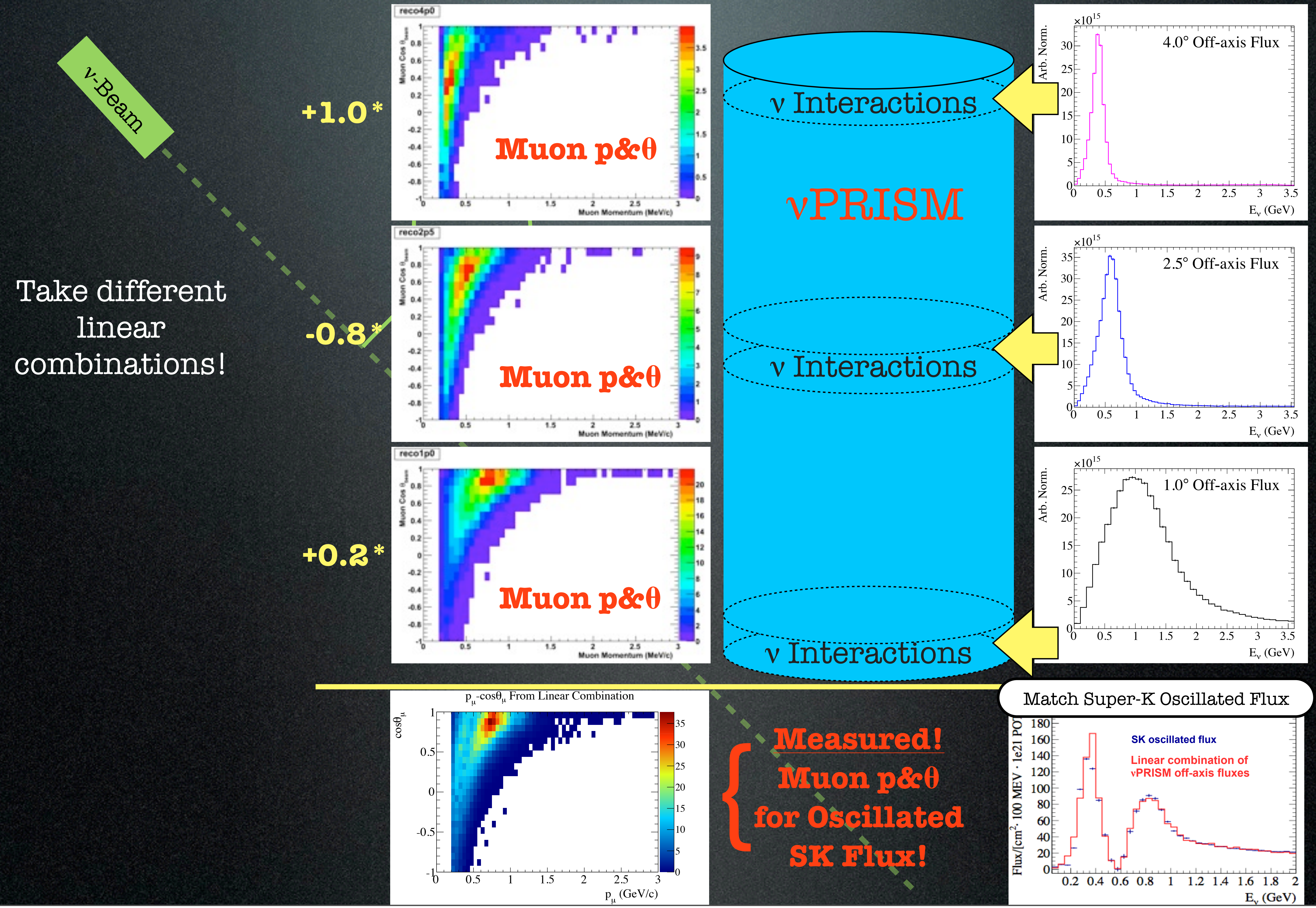


NuPRISM in Oscillation Analyses

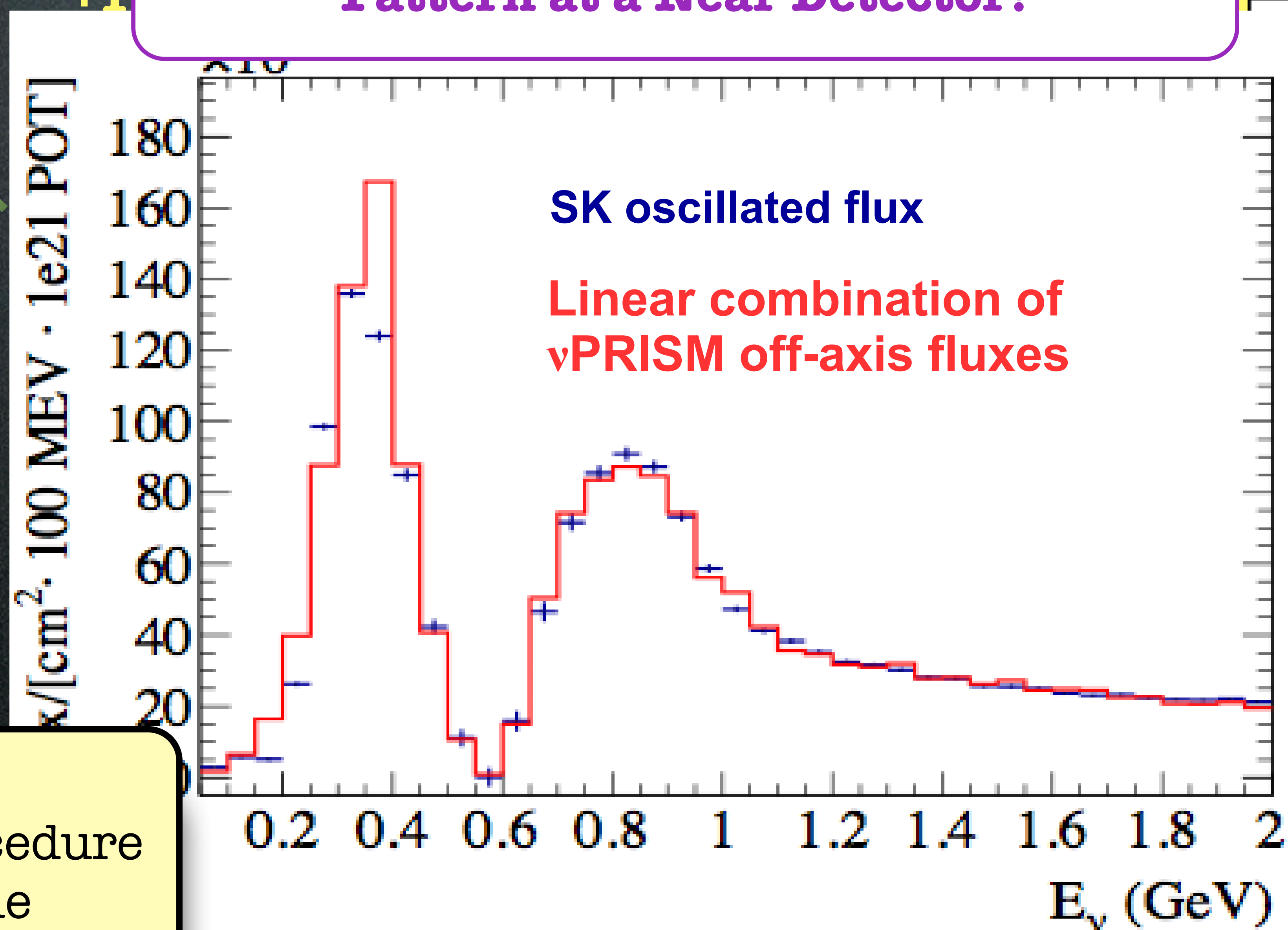


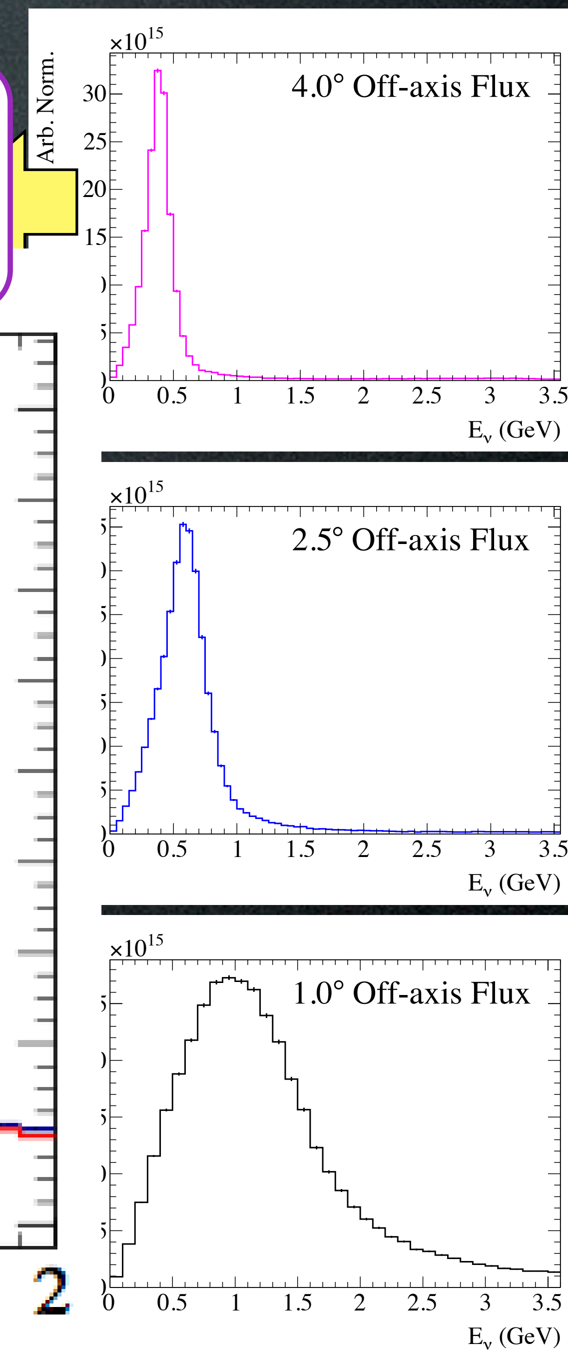
NuPRISM in Oscillation Analyses

ν-Beam

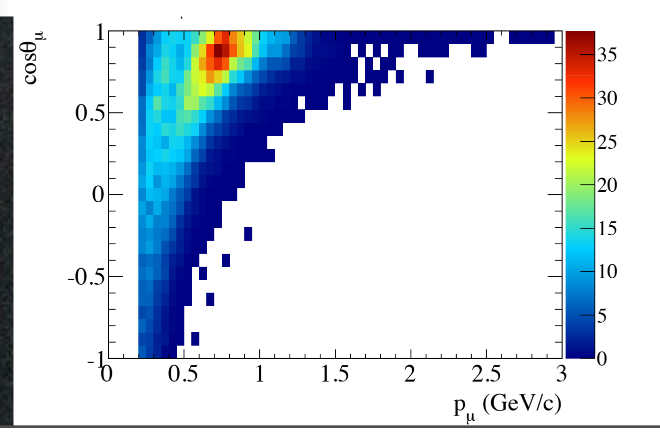
Reproduce Super-K Oscillation Pattern at a Near Detector!

Take different linear combinations!

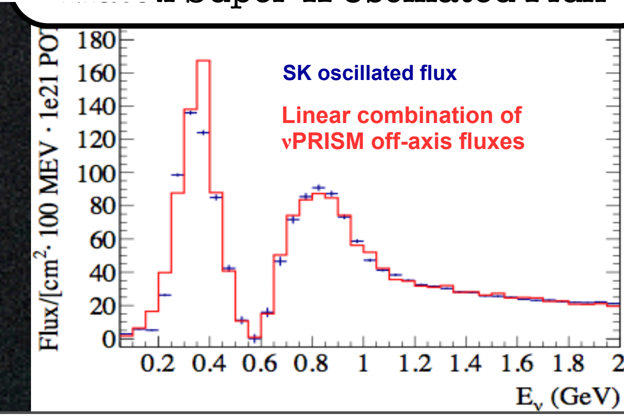




This is the procedure used for the **T2K/nuPRISM** ν_μ disappearance analysis

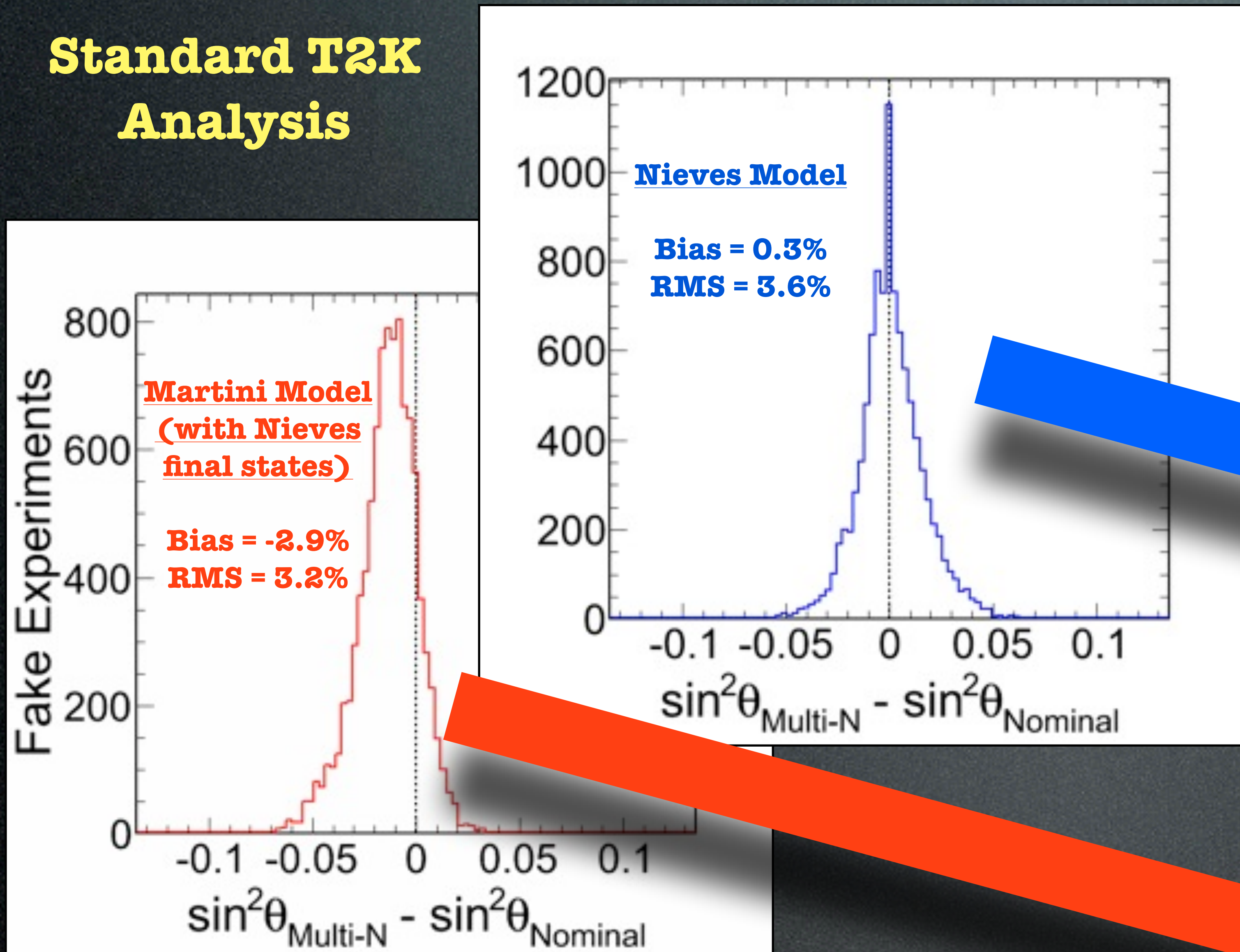


Measured! Muon p&θ for Oscillated SK Flux!



νPRISM ν_μ Disappearance Constraint

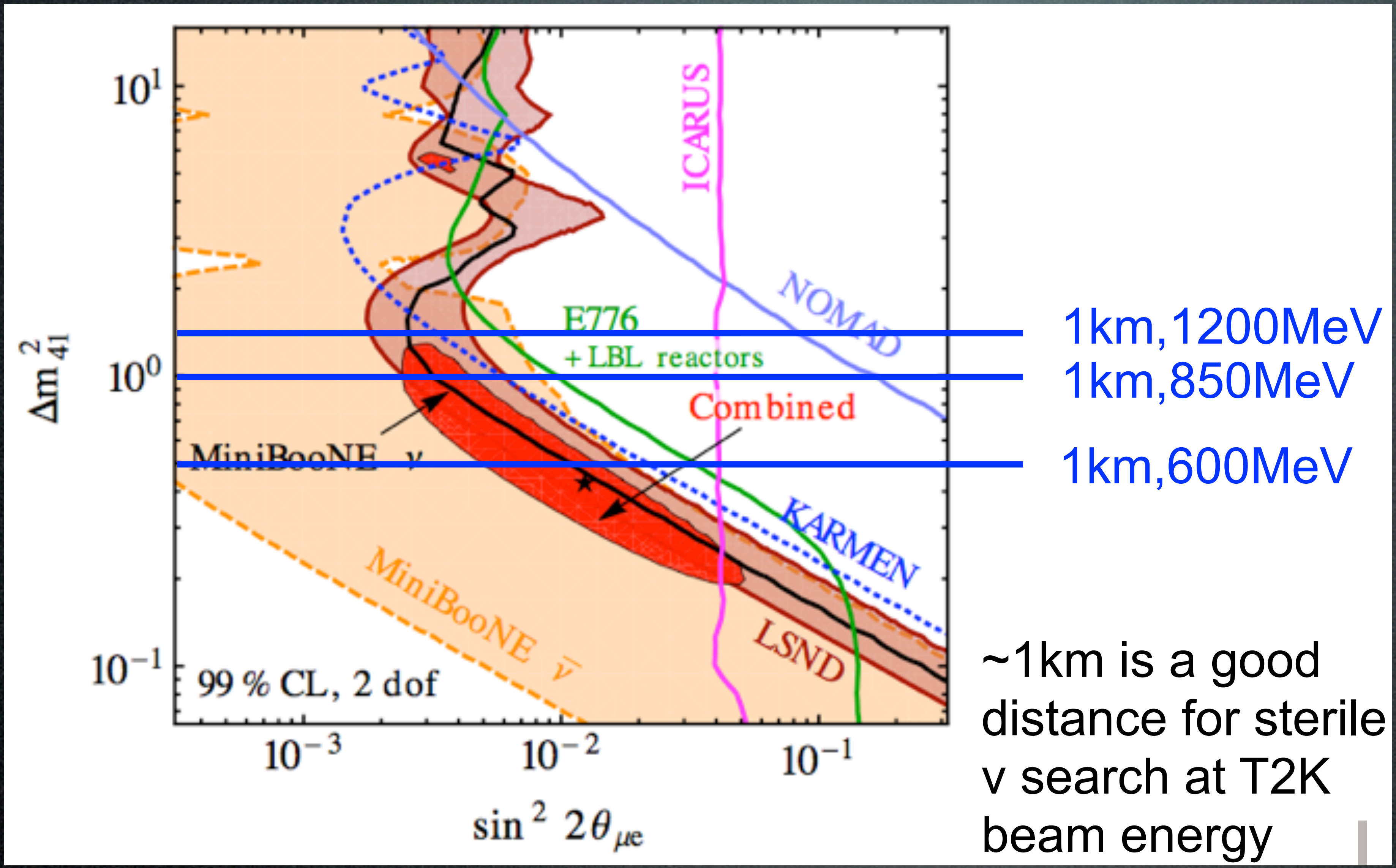
Standard T2K Analysis



νPRISM Analysis

- Fake data studies show the bias in θ_{23} is reduced from **4.3%**/**3.6%** to **1.2%**/**1.0%**
- More importantly, this is now based on a **data constraint**, rather than a model-based guess
- Expect the NuPRISM constraints to get significantly better as additional constraints are implemented (very conservative errors)

Sterile Neutrinos



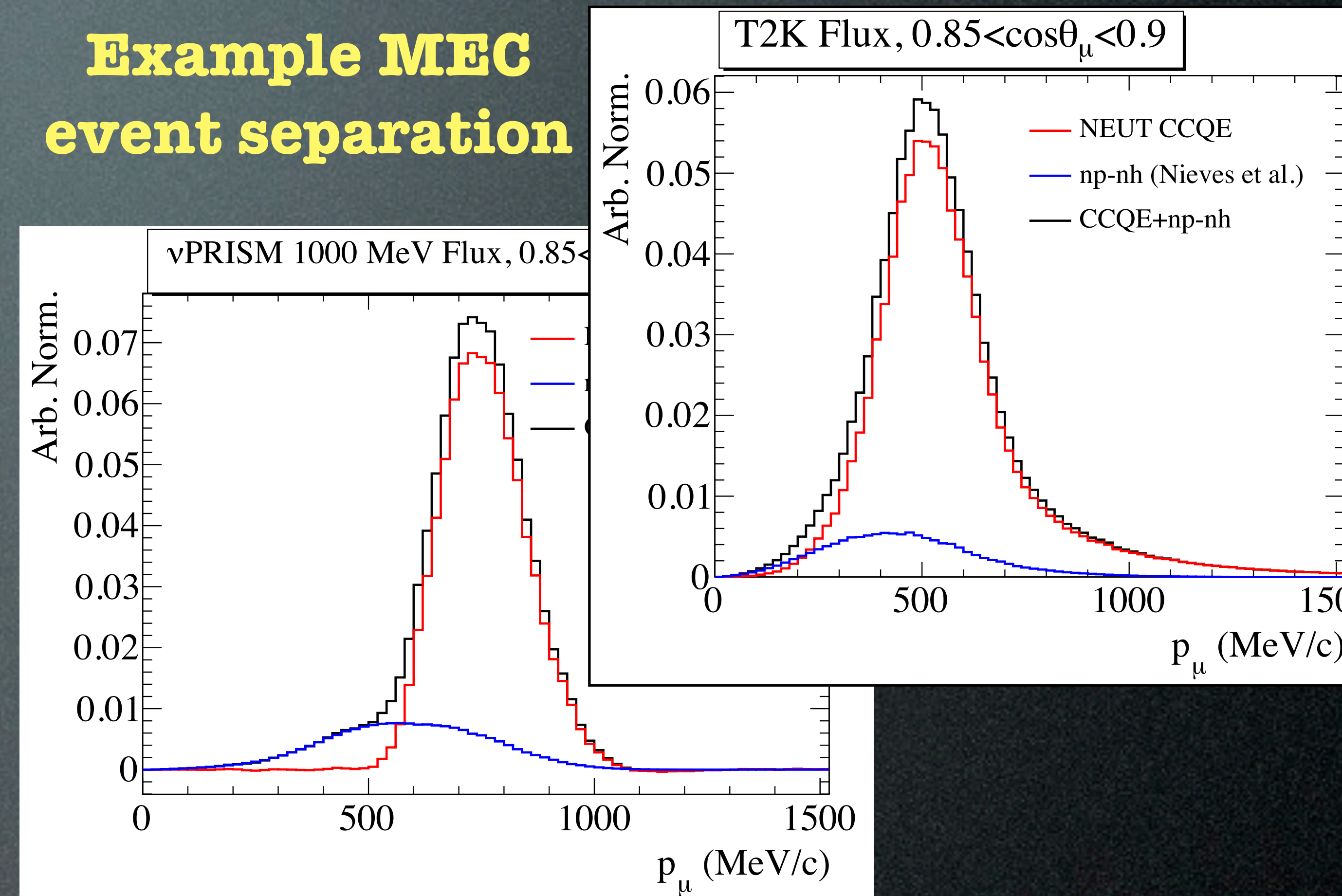
More details this afternoon!

- The 1 km baseline is ideal for sterile neutrinos
  - Like Fermilab SB, but with a much bigger detector (5kt vs 0.6kt)
  - Many repeated measurements for varying energy spectra
    - Signal and background events vary differently across the detector
    - Continuously sample a variety of L/E values

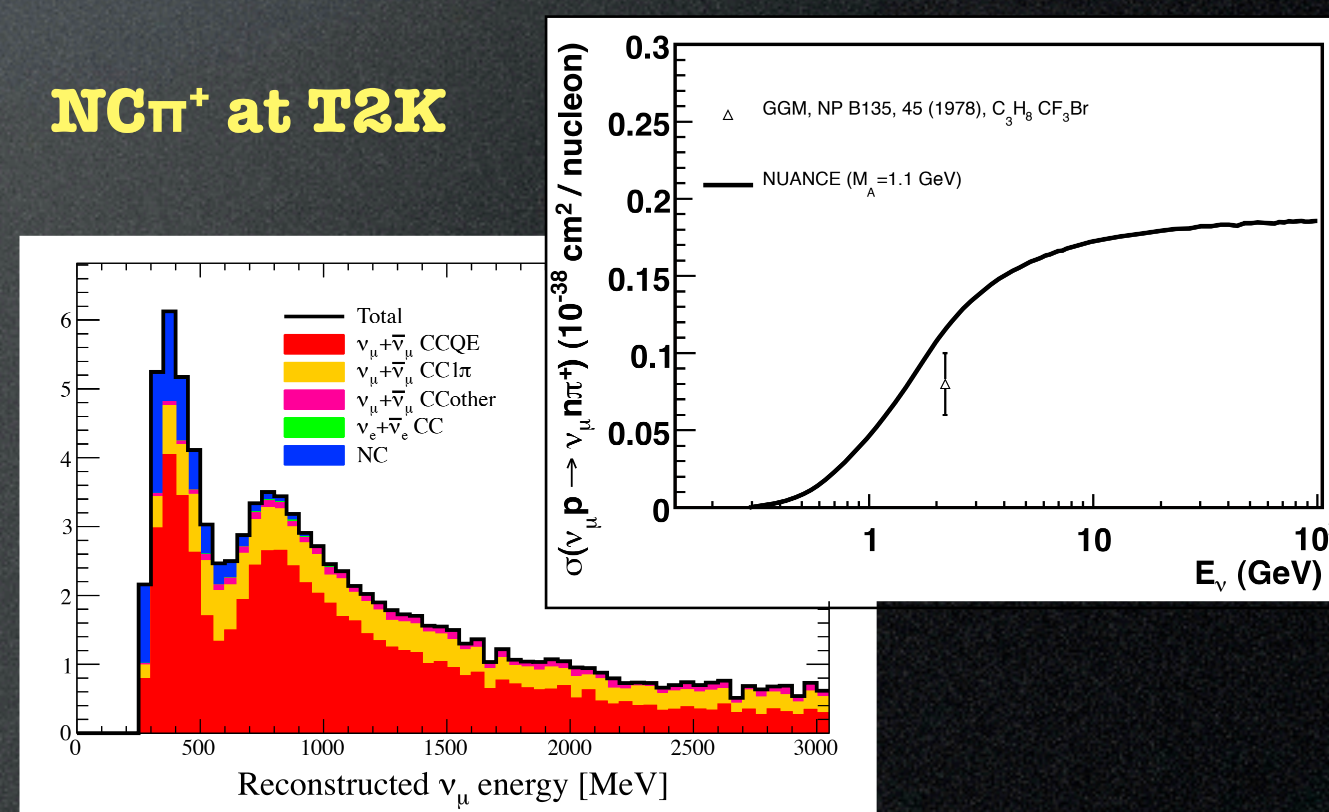
ν Cross Section Measurements

- Mono-energetic neutrino beams are ideal for measuring neutrino cross sections
    - Can provide a strong constraint on new models
- T2K ν_μ disappearance is subject to large NCπ^+ uncertainties
    - 1 existing measurement
    - NuPRISM can place a strong constraint on this process vs E_ν

Example MEC event separation

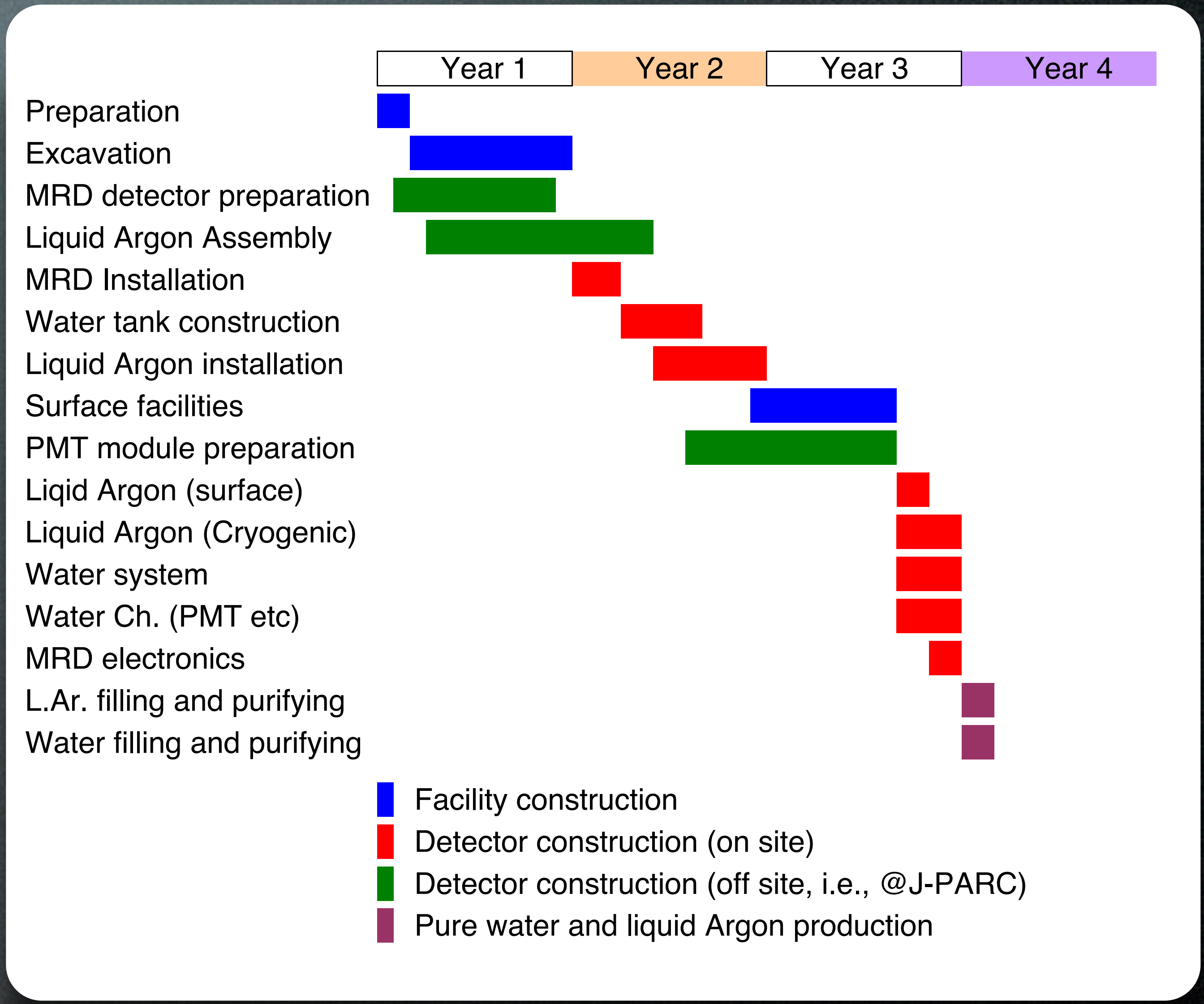


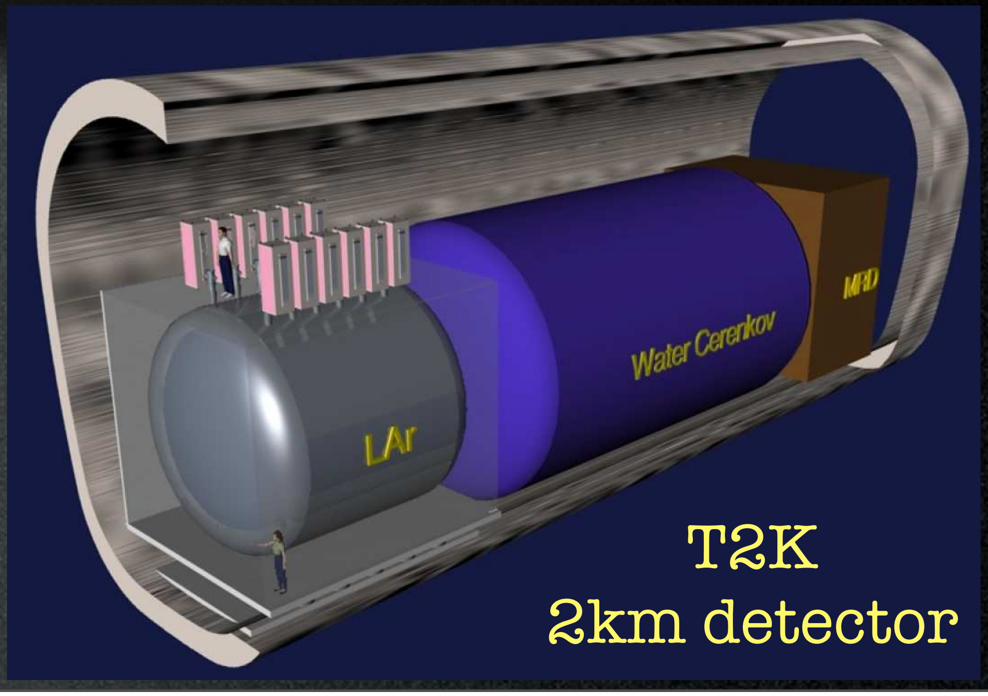
NCπ^+ at T2K



Timescales

- The T2K 2 km detector provides a
- NuPRISM construction time is faster
  - Same pit depth as the 2km detector, but no excavation of a large cavern at the bottom of the pit
  - Smaller instrumented volume
  - No LAr or MRD detector
- < 3 year timescale from approval to data taking
- Goal is to start data taking in time for the J-PARC 700kW beam (2018?)
  - Ideally, ground breaking would start in 2016





Current Status

- A Letter of Interest (LoI) was submitted to the J-PARC PAC in November 2014
    - arXiv:1412.3086
    - Full proposal to be submitted in June
- 50 physicists (and growing)
    - Several non-T2K members have joined
    - Room for many more
- Total cost is $15-$20M
    - US can make a big impact for <10% of the total project cost
    - US contributions can also include PMTs from MiniBooNE or Daya Bay

Spokespeople

Letter of Intent to Construct a nuPRISM Detector in the J-PARC Neutrino Beamline

S. Bhadra,[24] A. Blondel,[3] S. Bordoni,[5] A. Bravar,[3] C. Bronner,[9] J. Caravaca Rodríguez,[5] M. Dziewiecki,[23] T. Feusels,[1] G.A. Fiorentini Aguirre,[24] M. Friend,[4,*] L. Haegel,[3] M. Hartz,[8,22] R. Henderson,[22] T. Ishida,[4,*] M. Ishitsuka,[20] C.K. Jung,[11,†] A.C. Kaboth,[6] H. Kakuno,[25] H. Kamano,[13] A. Konaka,[22] Y. Kudenko,[7,‡] M. Kuze,[20] T. Lindner,[22] K. Mahn,[10] J.F. Martin,[21] J. Marzec,[23] K.S. McFarland,[15] S. Nakayama,[18,†] T. Nakaya,[9,8] S. Nakamura,[12] Y. Nishimura,[19] A. Rychter,[23] F. Sánchez,[5] T. Sato,[12] M. Scott,[22] T. Sekiguchi,[4,*] M. Shiozawa,[18,8] T. Sumiyoshi,[25] R. Tacik,[14,22] H.K. Tanaka,[18,†] H.A. Tanaka,[1,§] S. Tobayama,[1] M. Vagins,[8,2] J. Vo,[5] D. Wark,[16] M.O. Wascko,[6] M.J. Wilking,[11] S. Yen,[22] M. Yokoyama,[17,†] and M. Ziembicki[23]

(The nuPRISM Collaboration)

[1] *University of British Columbia, Department of Physics and Astronomy, Vancouver, British Columbia, Canada*
[2] *University of California, Irvine, Department of Physics and Astronomy, Irvine, California, U.S.A.*
[3] *University of Geneva, Section de Physique, DPNC, Geneva, Switzerland*
[4] *High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan*
[5] *Institut de Fisica d'Altes Energies (IFAE), Bellaterra (Barcelona), Spain*
[6] *Imperial College London, Department of Physics, London, United Kingdom*
[7] *Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia*
[8] *Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, University of Tokyo, Kashiwa, Chiba, Japan*
[9] *Kyoto University, Department of Physics, Kyoto, Japan*
[10] *Michigan State University, Department of Physics and Astronomy, East Lansing, Michigan, U.S.A.*
[11] *State University of New York at Stony Brook, Department of Physics and Astronomy, Stony Brook, New York, U.S.A.*
[12] *Osaka University, Department of Physics, Osaka, Toyonaka, Japan*
[13] *Osaka University, Research Center for Nuclear Physics(RCNP), Ibaraki, Osaka, Japan*
[14] *University of Regina, Department of Physics, Regina, Saskatchewan, Canada*
[15] *University of Rochester, Department of Physics and Astronomy, Rochester, New York, U.S.A.*
[16] *STFC, Rutherford Appleton Laboratory, Harwell Oxford, and Daresbury Laboratory, Warrington, United Kingdom*
[17] *University of Tokyo, Department of Physics, Tokyo, Japan*
[18] *University of Tokyo, Institute for Cosmic Ray Research, Kamioka Observatory, Kamioka, Japan*
[19] *University of Tokyo, Institute for Cosmic Ray Research, Research Center for Cosmic Neutrinos, Kashiwa, Japan*
[20] *Tokyo Institute of Technology, Department of Physics, Tokyo, Japan*
[21] *University of Toronto, Department of Physics, Toronto, Ontario, Canada*
[22] *TRIUMF, Vancouver, British Columbia, Canada*
[23] *Warsaw University of Technology, Institute of Radioelectronics, Warsaw, Poland*
[24] *York University, Department of Physics and Astronomy, Toronto, Ontario, Canada*
[25] *Tokyo Metropolitan University, Department of Physics, Tokyo, Japan*

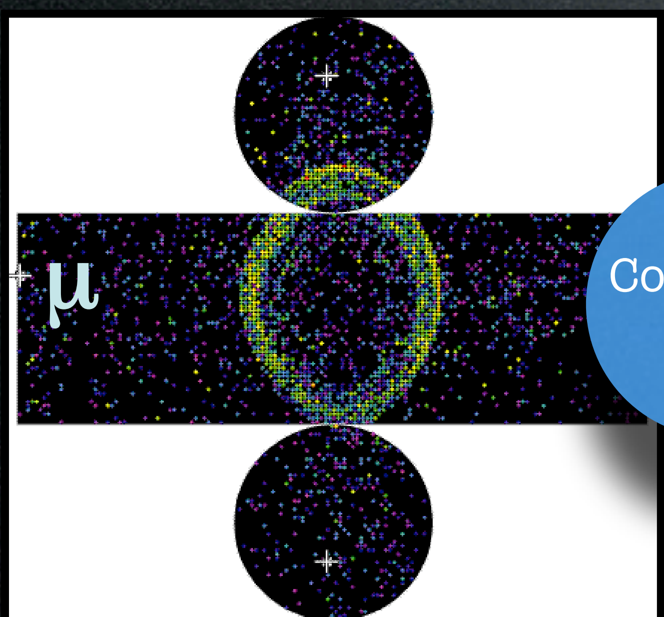
Summary

- NuPRISM is the only experimental mechanism that can largely remove neutrino interaction uncertainties from oscillation measurements
  - An experimental solution to the neutrino energy measurement problem!
  - Important for T2K
  - Essential for next generation experiments
- Many other important measurements (sterile-ν, unique cross sections)
- NuPRISM is a stand-alone experimental collaboration of >50 physicists
  - Several members that are not T2K members
- Full proposal will be submitted to the J-PARC PAC in June
  - With stage-1 approval, Japanese funding can be sought
    - Collaborators from KEK, ICRR, and several other Japanese institutions will host the project
- US can play a large role with a relatively modest (< 10%) contribution to the project

Supplement

How We Typically Perform Oscillation Analyses

Observed far detector signal:
1-ring muon events



Composed Of:

CCQE: $\mu^- + p$ (p unobserved)

CCπ⁺: $\mu^- + N + \pi^+$ (p, π^+ unobserved)

CCDIS: $\mu^- + X$ (X unobserved)

NCπ⁺: $\pi^+ + n$ (π^+ misidentified, n unobserved)

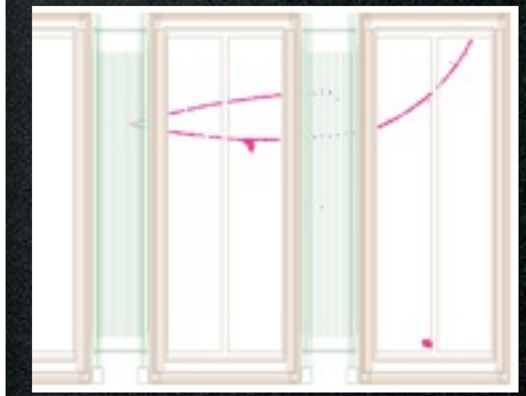
...

Nuclear model

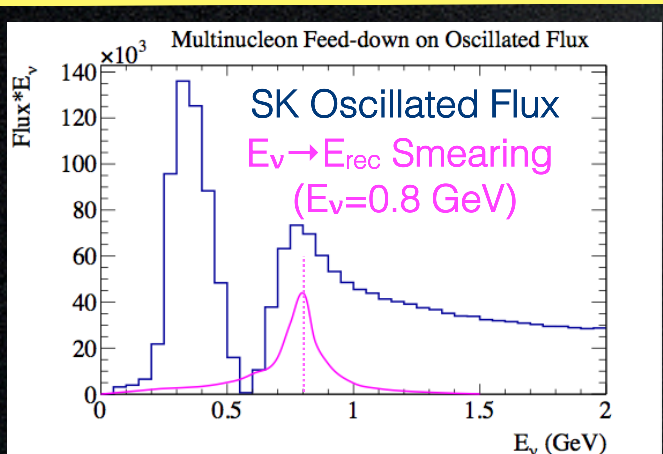
Predicted by poorly understood models

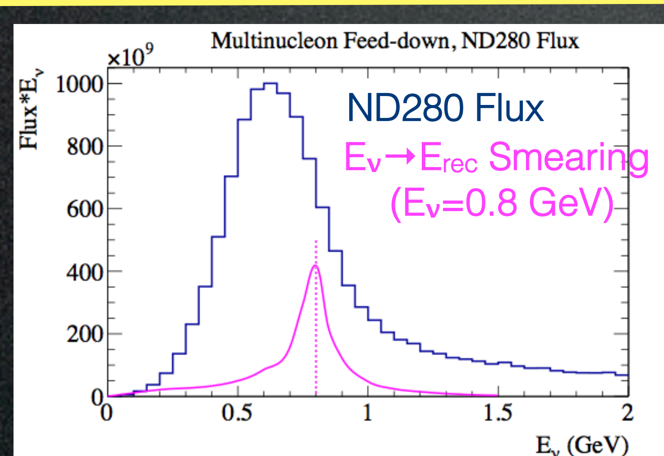
Parameter	E_ν Range	Nominal	Error	Class
M_A^{QE}	all	1.21 GeV/c^2	0.45	shape
M_A^{RES}	all	1.41 GeV/c^2	0.11	shape
p_F ^{12}C	all	217 MeV/c	30	shape
E_B ^{12}C	all	25 MeV	9	shape
SF ^{12}C	all	0 (off)	1 (on)	shape
CC Other shape ND280	all	0.0	0.40	shape
Pion-less Δ Decay	all	0.0	0.2	shape
CCQE E1	$0 < E_\nu < 1.5$	1.0	0.11	norm
CCQE E2	$1.5 < E_\nu < 3.5$	1.0	0.30	norm
CCQE E3	$E_\nu > 3.5$	1.0	0.30	norm
CC1π E1	$0 < E_\nu < 2.5$	1.15	0.43	norm
CC1π E2	$E_\nu > 2.5$	1.0	0.40	norm
CC Coh	all	1.0	1.0	norm
NC1π^0	all	0.96	0.43	norm
NC 1$\pi^\pm$	all	1.0	0.3	norm
NC Coh	all	1.0	0.3	norm
NC other	all	1.0	0.30	norm
ν_μ/ν_e	all	1.0	0.03	norm
$\nu/\bar{\nu}$	all	1.0	0.40	norm

Simultaneously constrain flux and cross section parameters with a near detector



But the near and far fluxes are different!



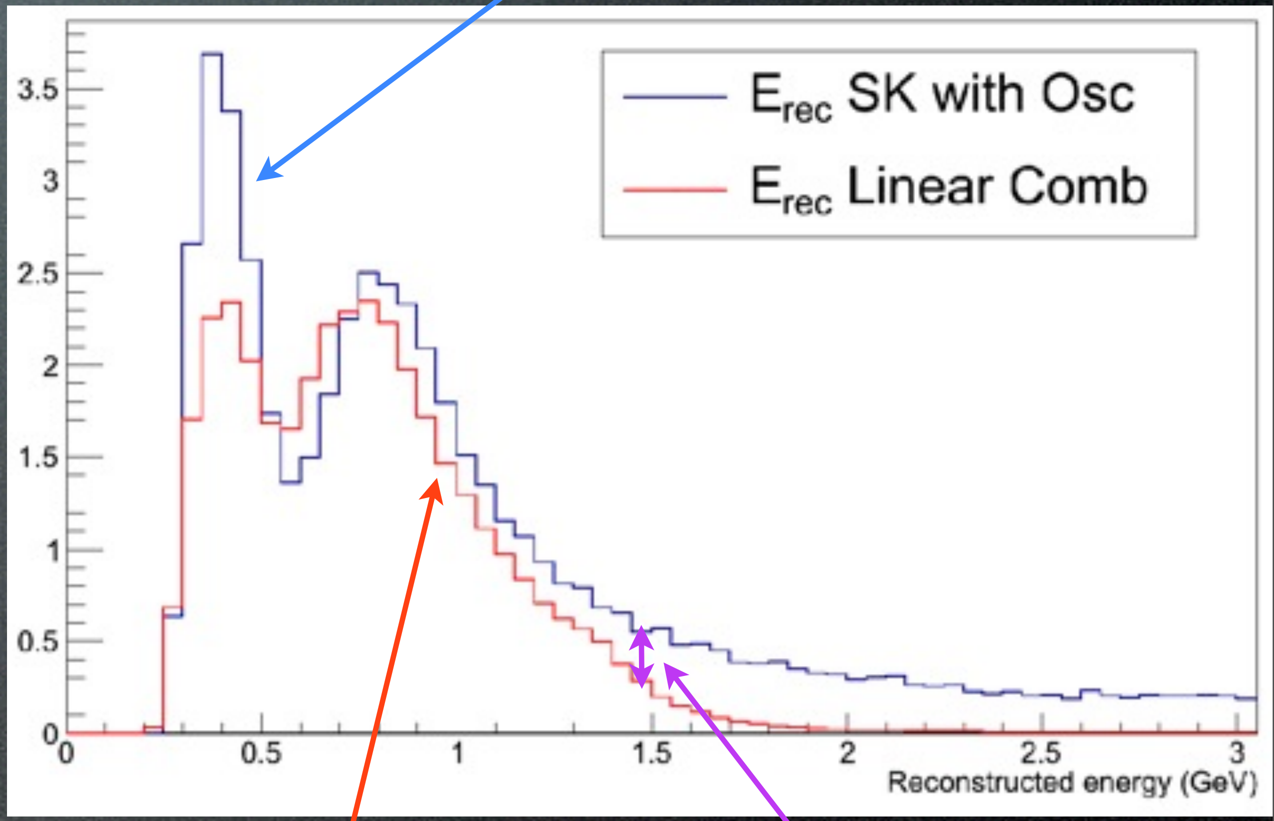


Goal of NuPRISM is to replace this procedure with a data measurement (to first order)

E_{rec} Distribution

- **For now, collapse 2D muon p,θ distribution into 1D E_{rec} plot**
- **Notice the NuPRISM and SK distributions disagree**
    - If they didn't, we would have no cross section systematic errors (modulo variations in the flux)
    - Differences are from detector acceptance & resolution, and imperfect flux fit
- **Super-K prediction is largely based on the directly-measured NuPRISM muon kinematics!**
    - Now, only a small amount of model extrapolation is needed
    - T2K measurements are now largely independent of cross section modeling!

Previously, the entire predicted E_{rec} distribution at Super-K was based on model extrapolation



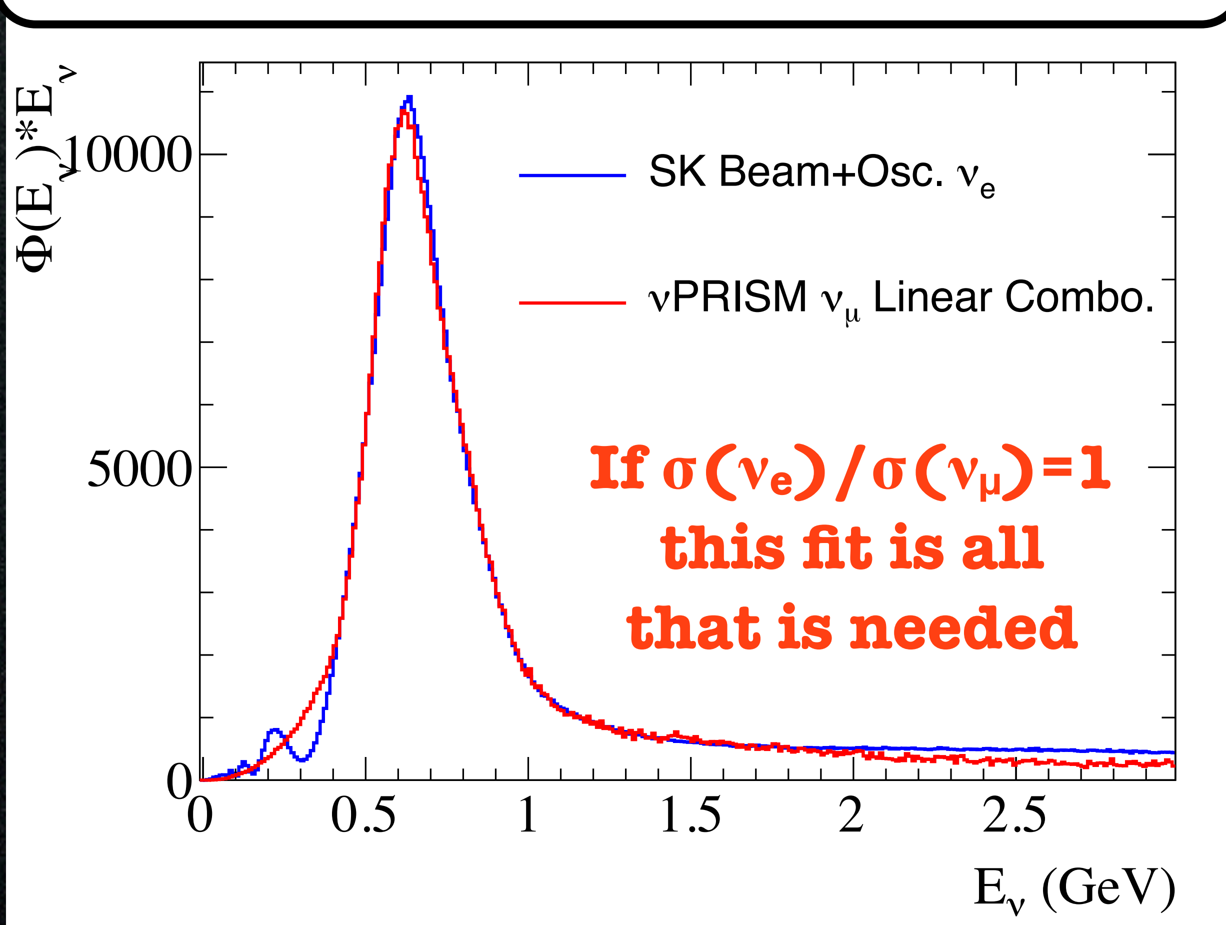
Now, NuPRISM directly measures most of this distribution

The remaining model-dependent correction factor (i.e. systematic uncertainty) is relatively small

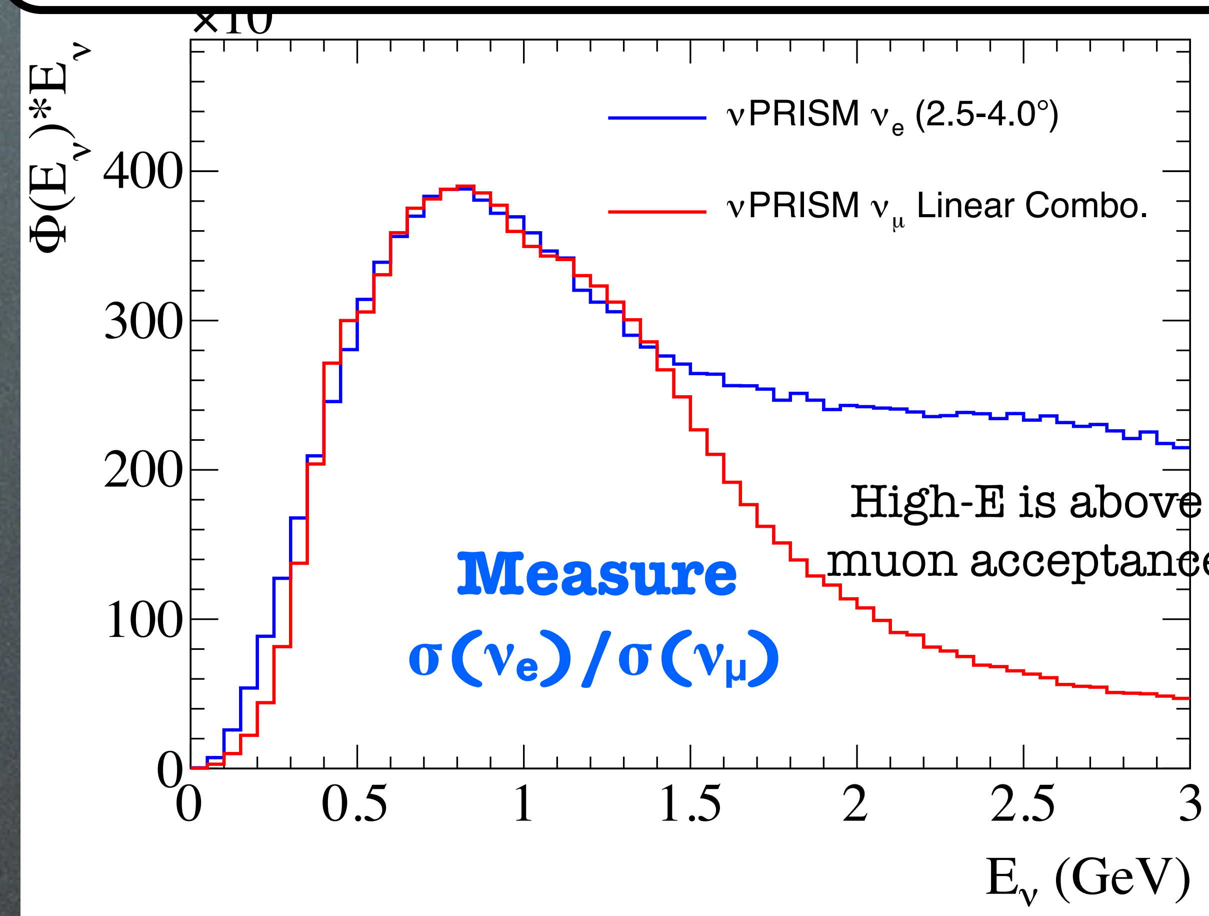
nuPRISM CPV (ν_e Appearance)

2 step approach:

Step 1: Measure **Super-K** ν_e response with nuPRISM ν_μ



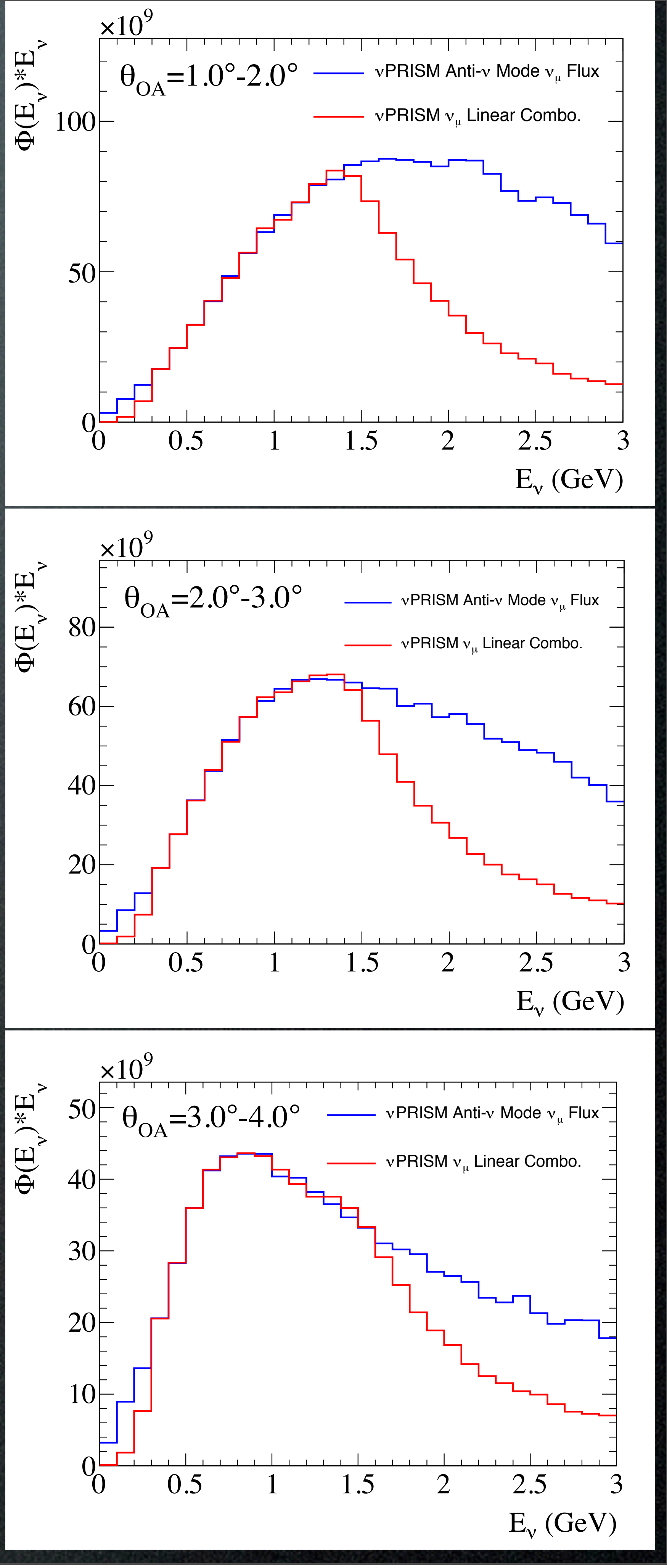
Step 2: Measure **nuPRISM** ν_e response with nuPRISM ν_μ



- Step 1 is the ν_e version of the ν_μ disappearance analysis
- Step 2 uses only nuPRISM to measure $\sigma(\nu_e)/\sigma(\nu_\mu)$
  - High energy disagreement is above muon acceptance
  - These plots show flux*E_ν, so difference is 1-ring μ events is smaller

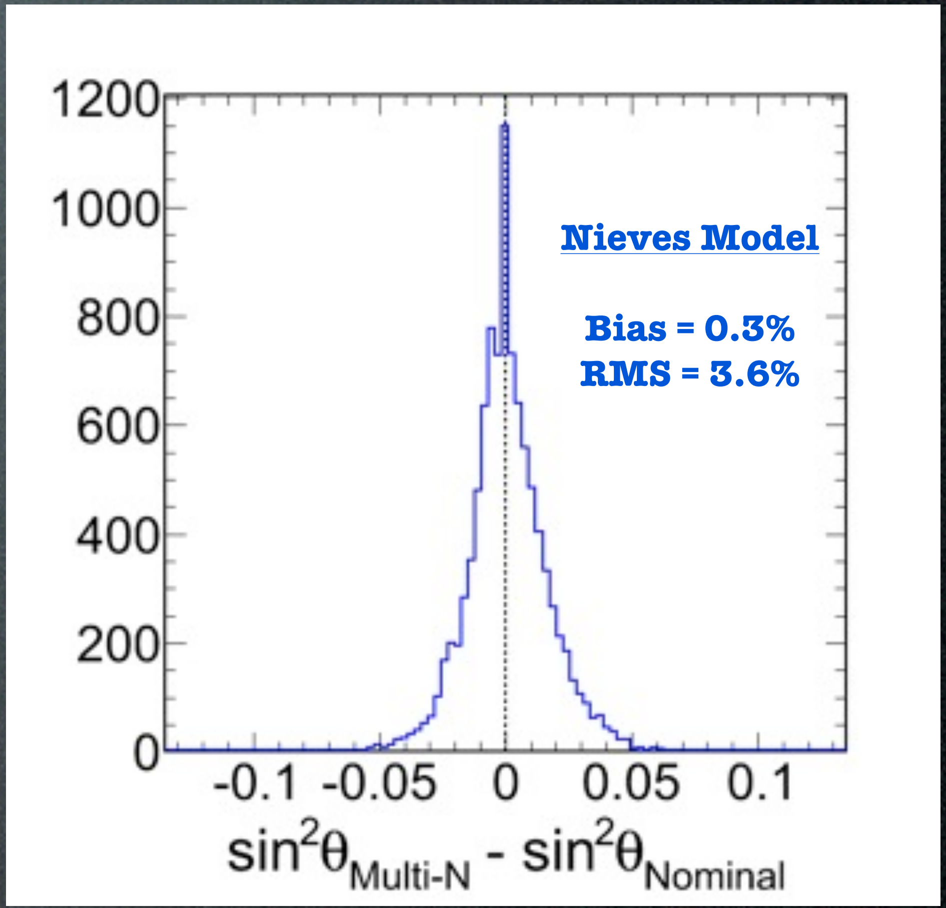
Anti-neutrinos

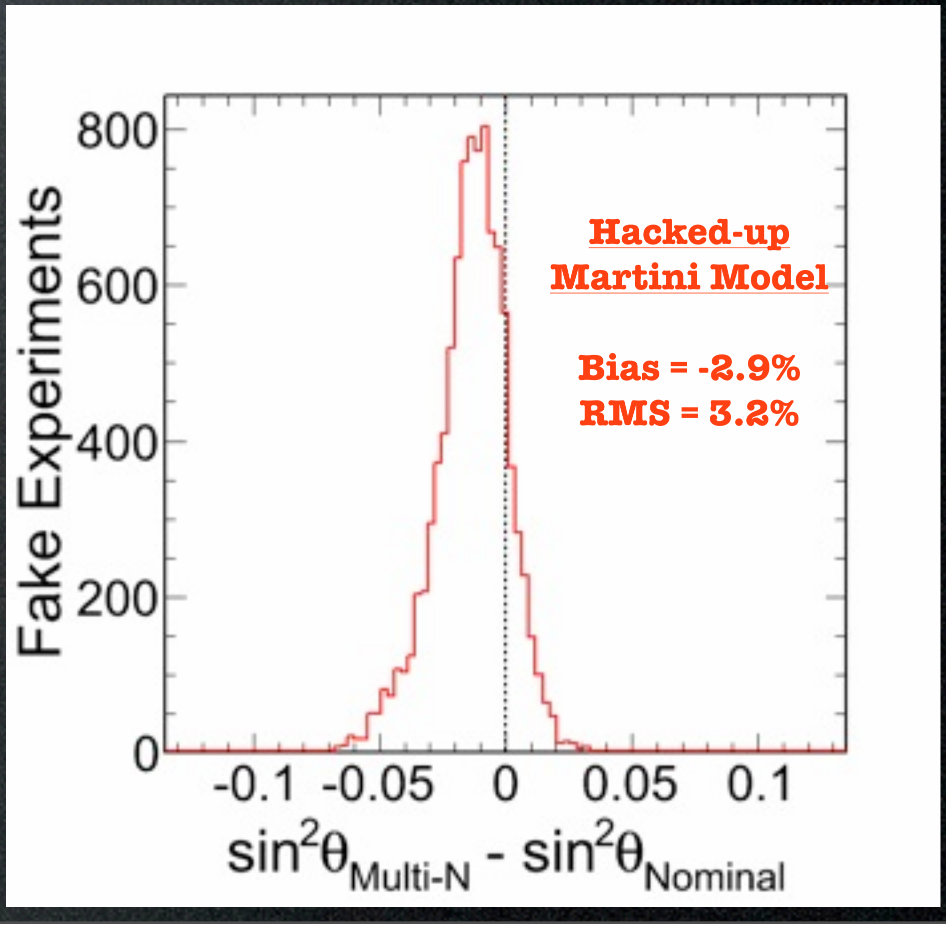
- T2K can switch between ν-mode and anti-ν-mode running by switching the beam focusing
- Anti-ν-mode analysis is the same as for neutrinos
    - Except with a much larger neutrino contamination
- Can use **ν-mode ν_μ data** to construct the **ν_μ background** in the **anti-ν-mode anti-ν_μ** data
    - Statistical separation of neutrinos from anti-neutrinos, rather than event-by-event sign selection
- After subtracting neutrino background, standard NuPRISM oscillation analyses can be applied to anti-neutrinos



Effect on T2K ν_μ Disappearance

- Create "fake data" samples with flux and cross section variations
  - With and without multi-nucleon events
- For each fake data set, full T2K near/far oscillation fit is performed
  - For each variation, plot difference with and without multi-nucleon events
- For Nieves model, "average bias" (RMS) = **3.6%**
- For Martini model, mean bias = -2.9%, RMS = 3.2%
  - Full systematic = $\sqrt{(2.9\%^2+3.2\%^2)}$ = **4.3%**
  - **This would be one of the largest systematic uncertainties**
- But this is just a comparison of 2 models
  - How much larger could the actual systematic uncertainty be?
- **We need a data-driven constraint!**





Interpreting Linear Combinations

- After νPRISM linear combination:
  - CC-ν_μ spectrum should reproduce oscillated far detector spectrum: **Good!**
  - NC-ν_μ backgrounds will also appear “oscillated”: **Bad!**
    - NC events are unaffected by oscillations at Super-K
- **NC events must be subtracted** at both Super-K and nuPRISM
  - Introduces cross section model dependence
- However, **NC backgrounds can be very well measured** using mono-energetic beams
  - Significantly reduces cross section model dependence
- In current analysis (see later slides), NC constraint has not yet been applied
  - **Conservative errors**

ν Energy Spectrum

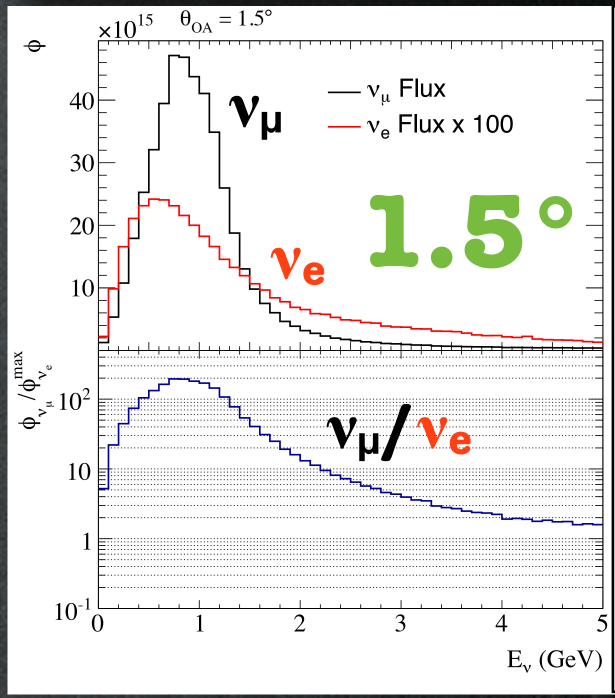
Flux < 1 GeV is dominated by π^+ decay

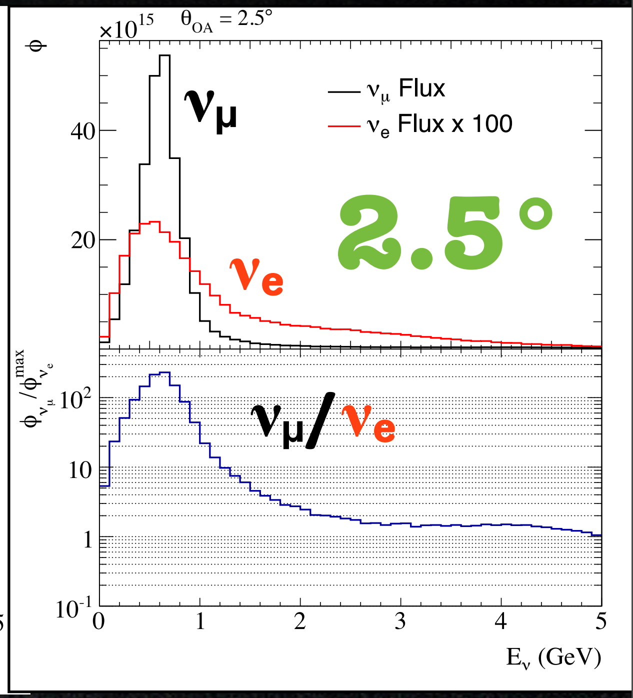
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

ν_μ produced in 2-body decay

ν_e produced in 3-body decay

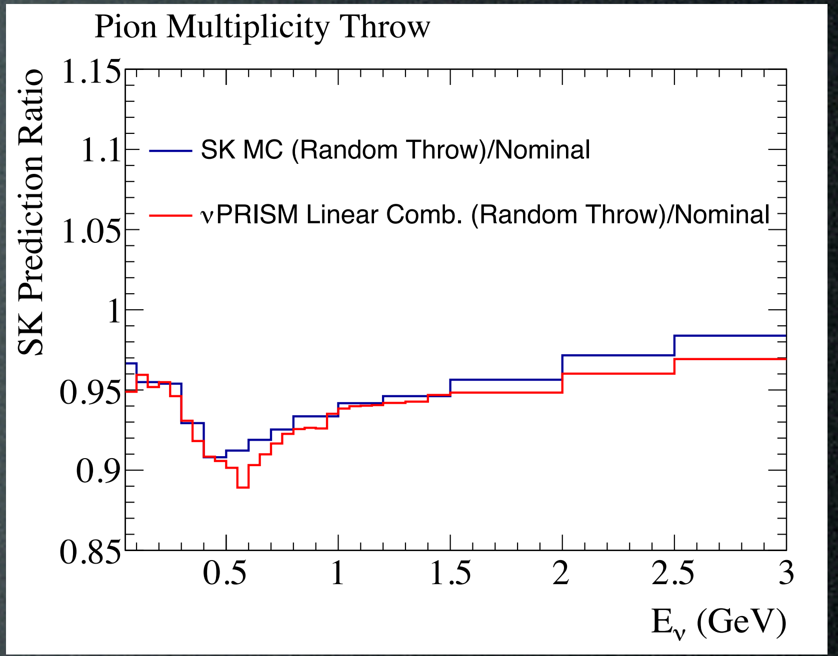
☞ ν_μ experience more off-axis affect

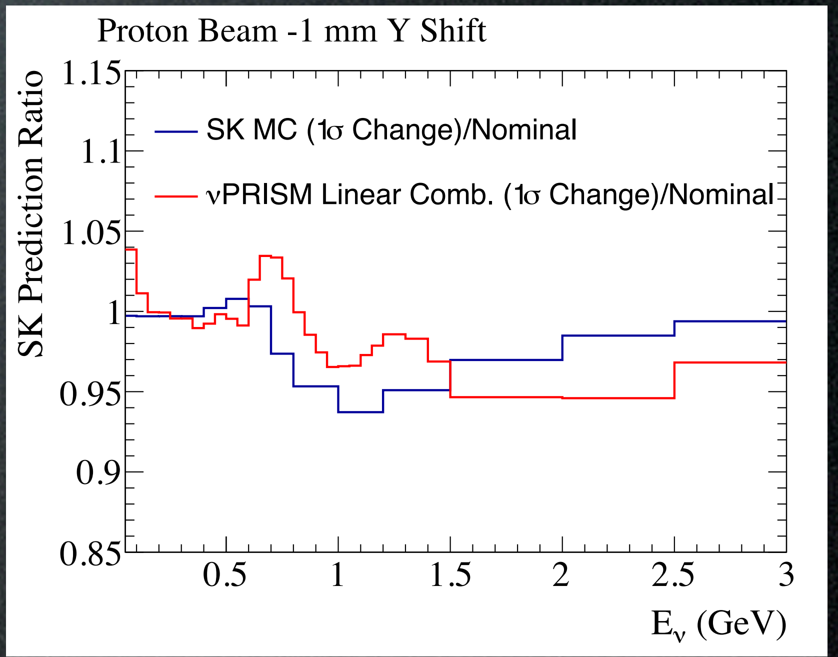


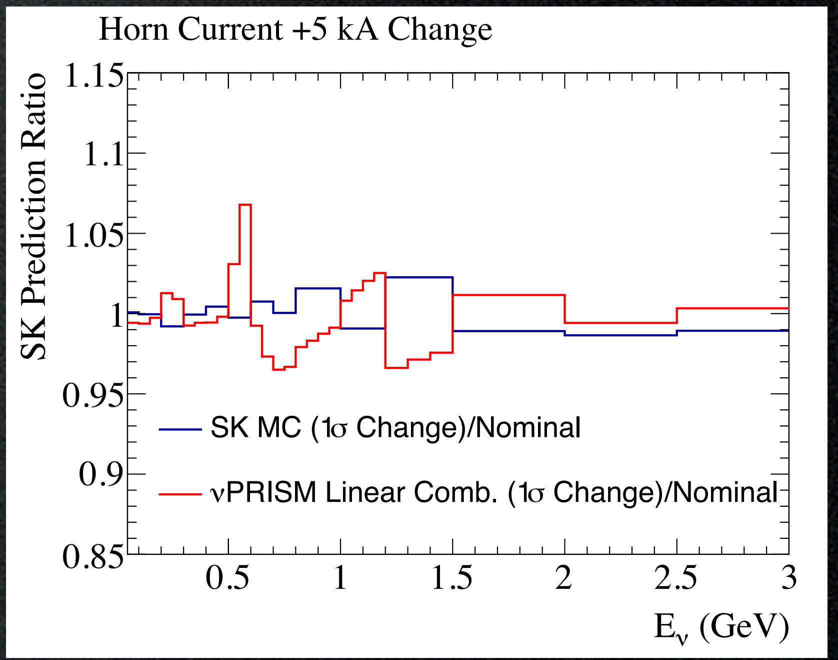


More on Beam Errors

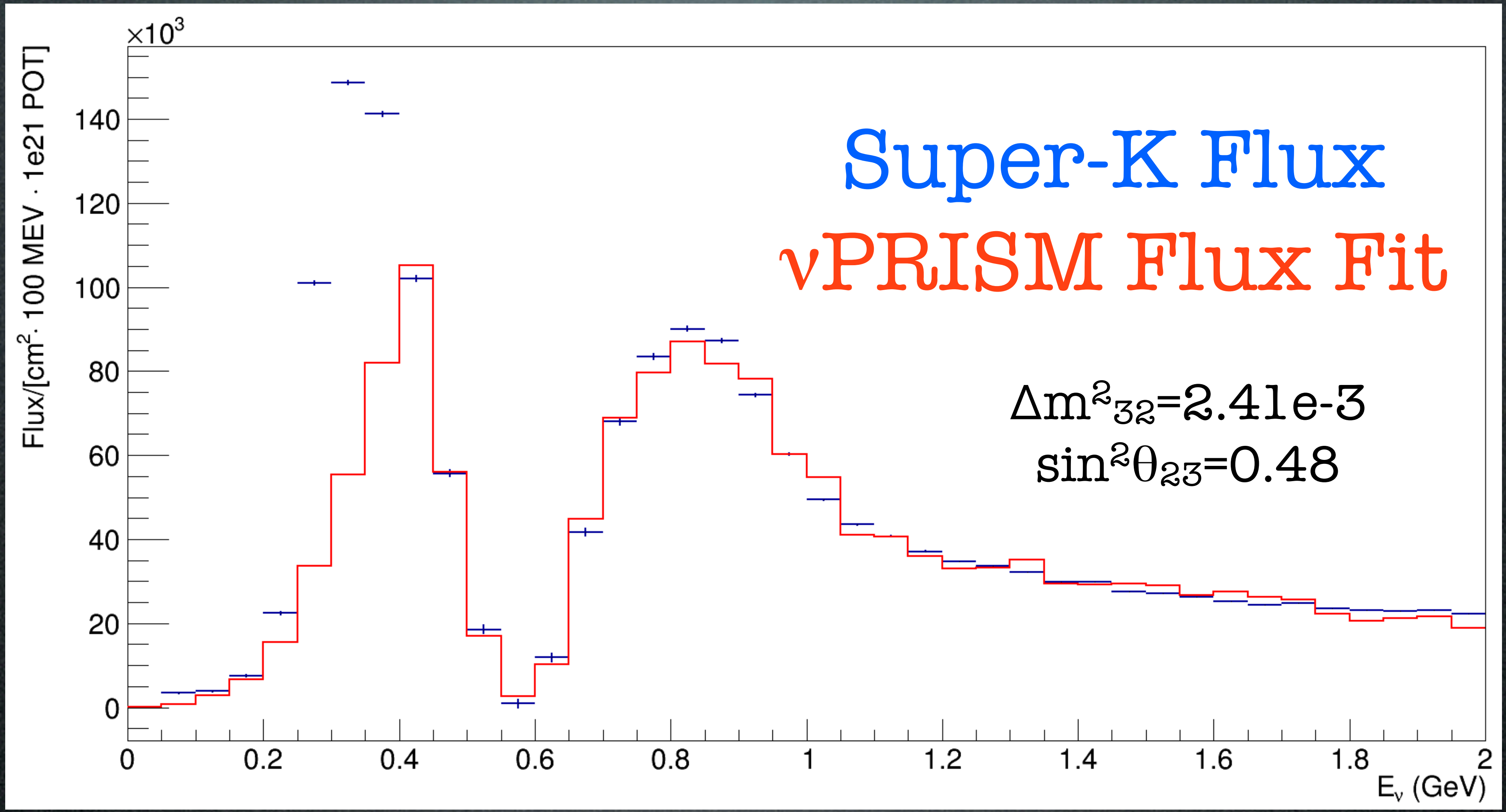
- Haven't we just replaced **unknown cross section errors** with **unknown flux errors**?
    - Yes! But only relative flux errors are important!
    - Cancelation exist between nuPRISM and far detector variations
- **Normalization uncertainties will cancel** in the νPRISM analysis
    - Cancelations persist, even for the νPRISM linear combination
    - Shape errors are most important
- For scale, **10% variation** near the dip means **~1% variation** in $\sin^2 2\theta_{23}$
    - Although this region is dominated by feed down
- Full flux variations are reasonable
    - No constraint used (yet) from existing near detector!







Flux Fit



- Fit for coefficients of 60 off-axis νPRISM slices to match a chosen Super-K oscillated spectrum
  - Fit between 400 MeV and 2 GeV
  - **Repeat this fit for every set of oscillation parameters**
- Notice disagreement at low energy
  - The most off-axis flux (4°) peaks at 380 MeV, so difficult to fit lower energies
  - Could extend detector further off-axis, but the low energy region is not very important to extract oscillation physics (e.g. nuclear feed-down not an issue)

nuPRISM Prediction for Super-K

- **Efficiency correction** is still needed for both νPRISM and Super-K
- νPRISM and Super-K have **different detector geometries**
  - Particles penetrate ID wall (and get vetoed) more often in nuPRISM
  - Particle ID degrades near the tank wall
- The efficiency correction is performed in **muon momentum and angle** to be as **model independent** as possible
  - This should be nearly a pure geometry correction
- For now, fit in Super-K E_{rec} distribution (in future, just use muon p,θ)

$$E^{SK}_{rec,j}(\Delta m^2_{32}, \theta_{23}) = \sum_{p,\theta} \left[\sum_{i}^{OAangles} c_i(\Delta m^2_{32}, \theta_{23}) \left(N^{obs}_{p\theta i} - B_{p\theta i}\right) \frac{\epsilon^{SK}_{p\theta}}{\epsilon^{\nu\mathrm{PRISM}}_{p\theta i}} \right] * M_{p\theta j}$$

predicted Super-K E_{rec} distribution

weight for off-axis slice, i

events in muon p,θ bin in slice, i

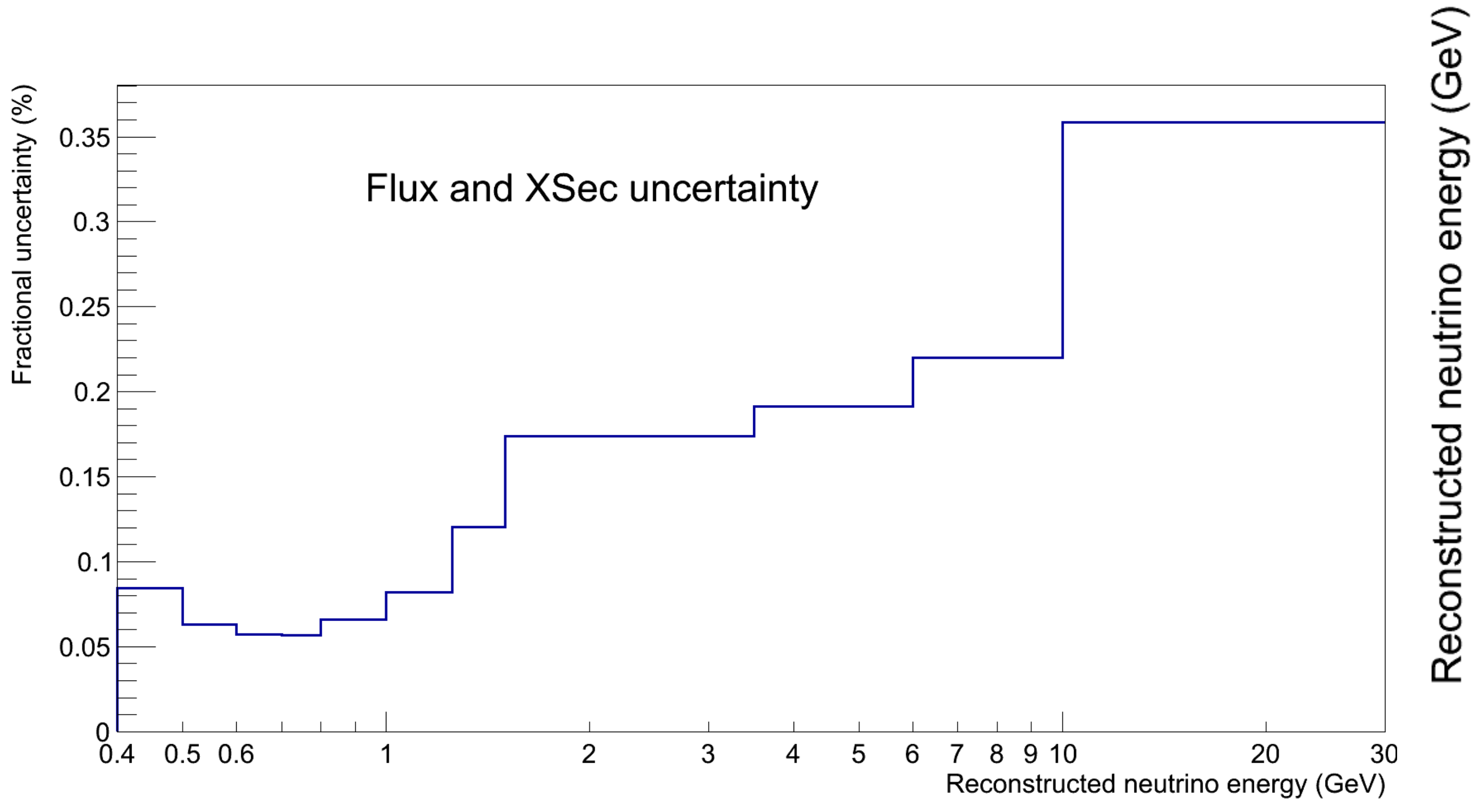
background subtraction

efficiency ratio

translation matrix p,θ → E_{rec}

Systematic Covariance Matrices

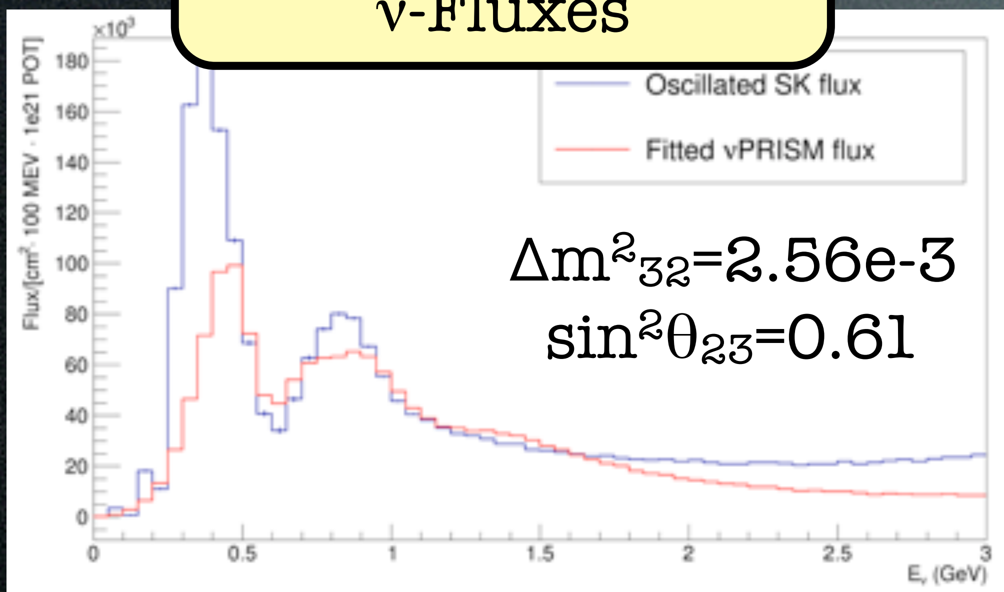
Analysis is performed in unequal-sized E_{rec} bins

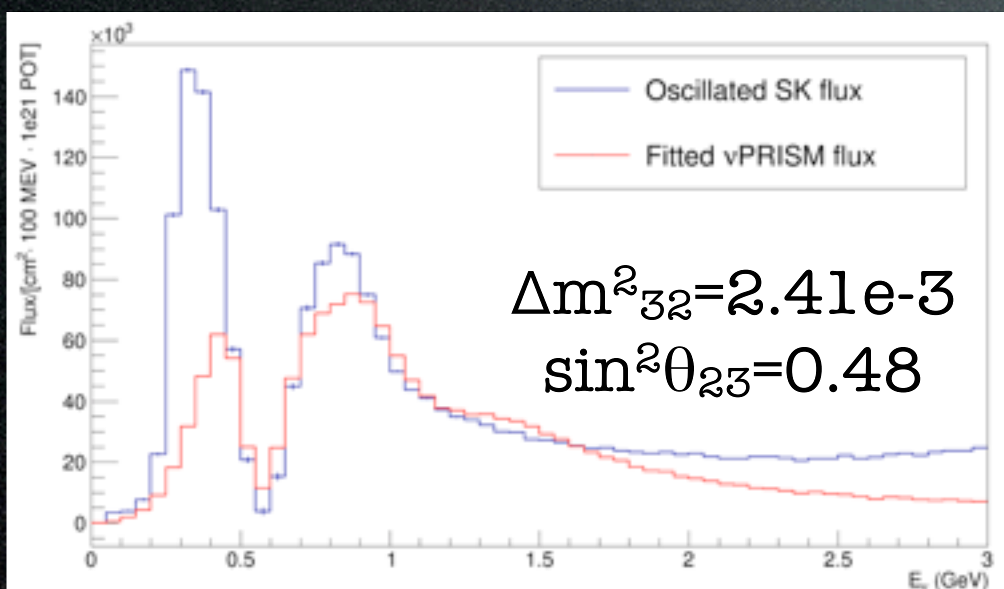


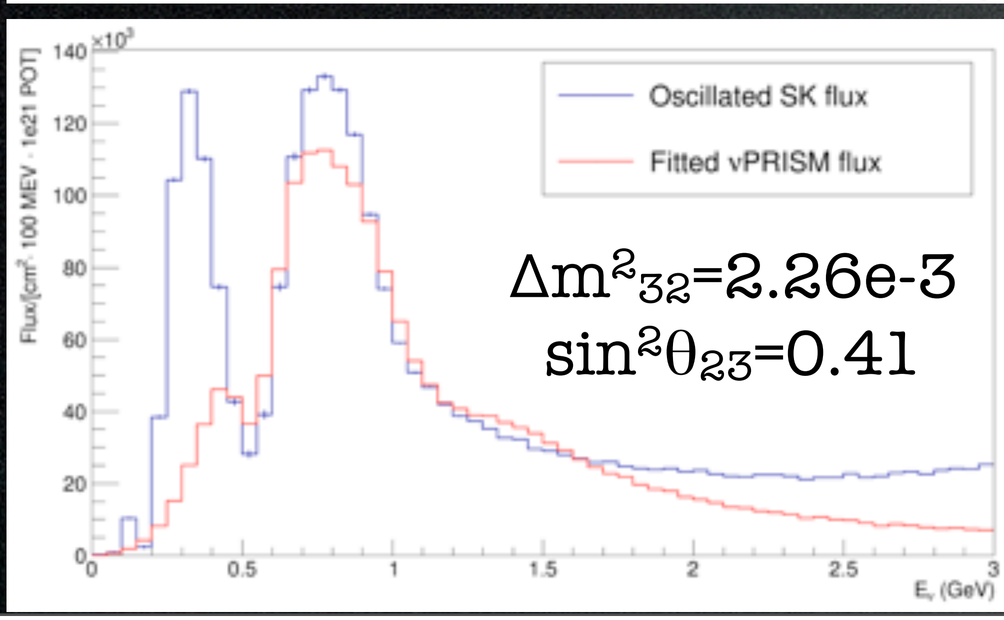
- Fractional uncertainties are shown (normalized to bin content)
- At high energies, νPRISM provides no constraint
  - Detector acceptance: all muons exit the inner detector
  - Subject to full flux & cross section uncertainties
- Bin 3 (600-700 MeV) has a 6% uncertainty

Smoothed ν-Flux Fits

ν-Fluxes

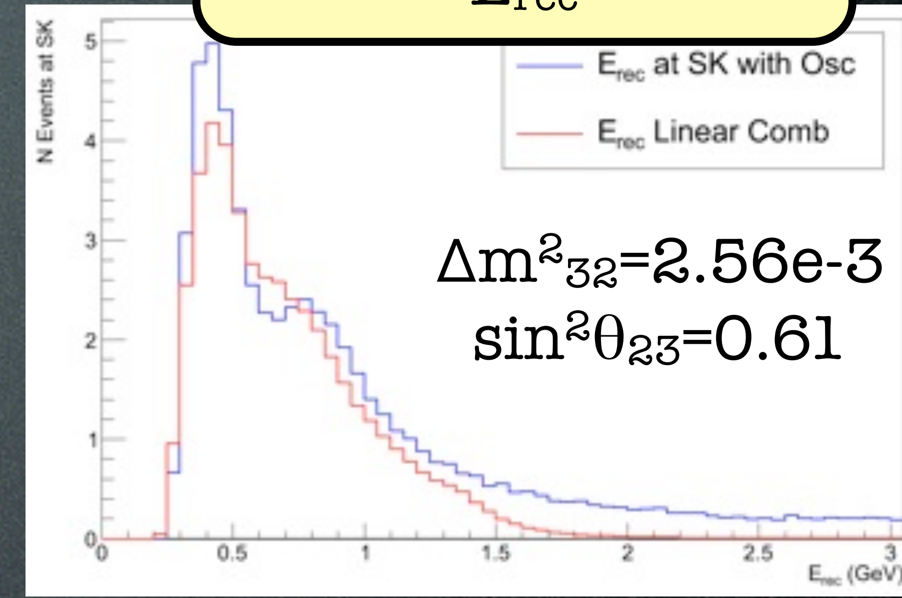


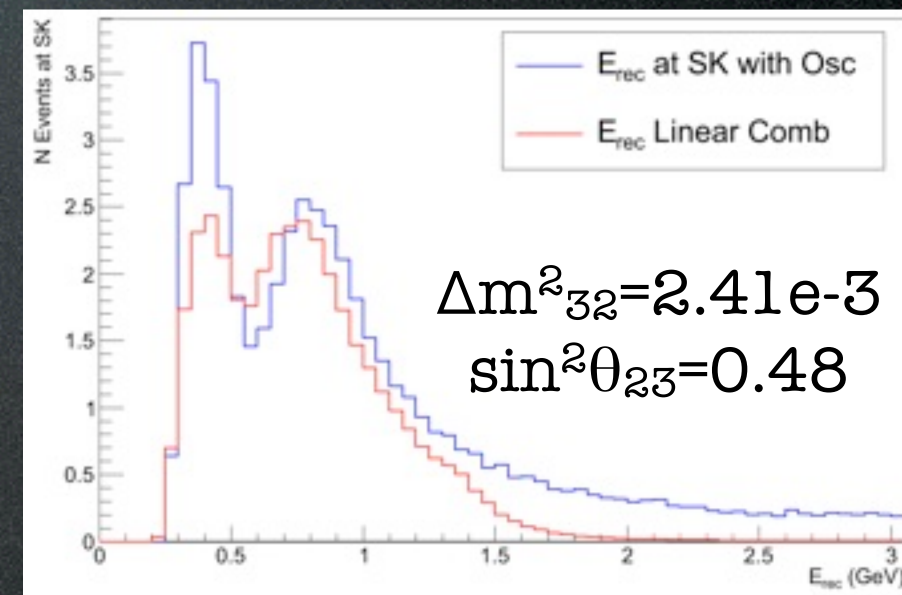


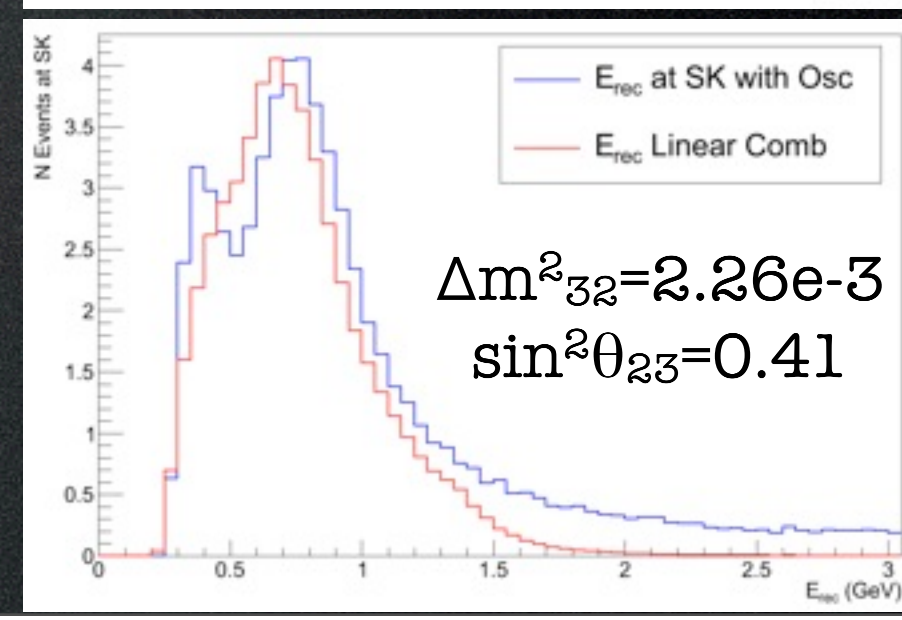


- Smoothed flux fits do not match as well
  - Easy to improve, if necessary
- However, very small increase to systematic uncertainties
  - Flux systematic variations are large
- Fits can be improved
  - Smoothness can be relaxed near fast-changing features
  - Off-axis angle bins need not be equal size

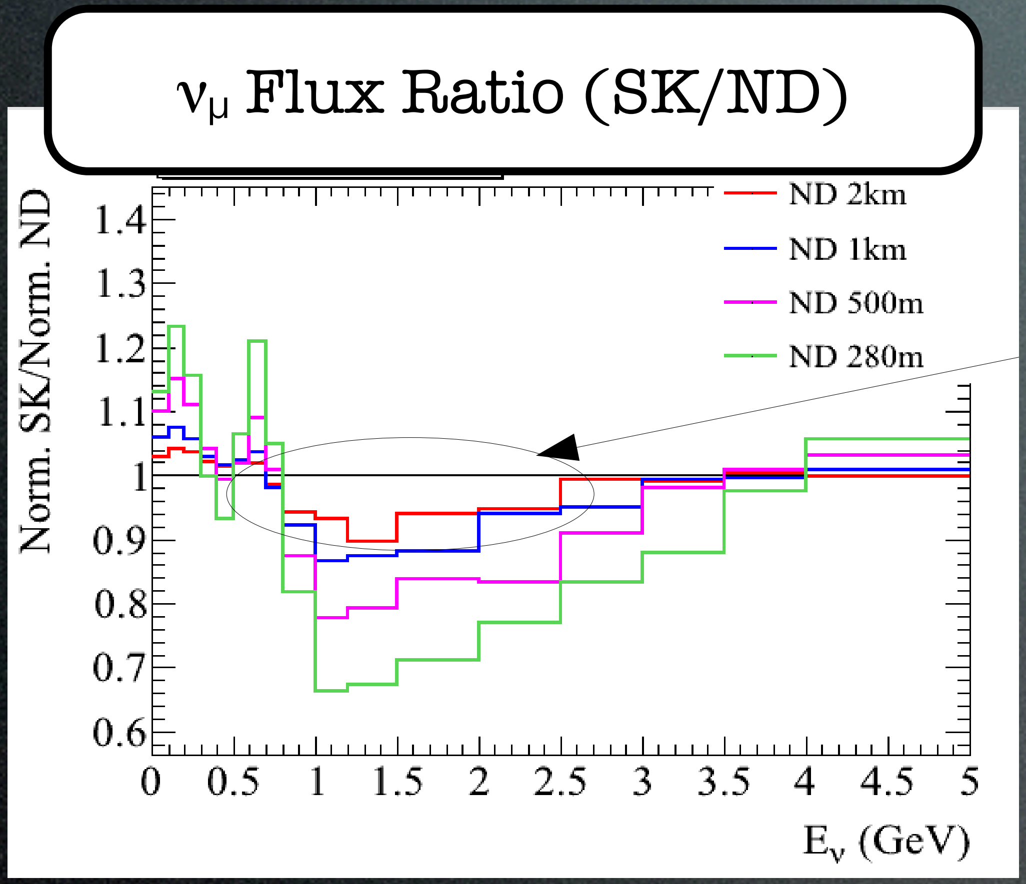
E_{rec}

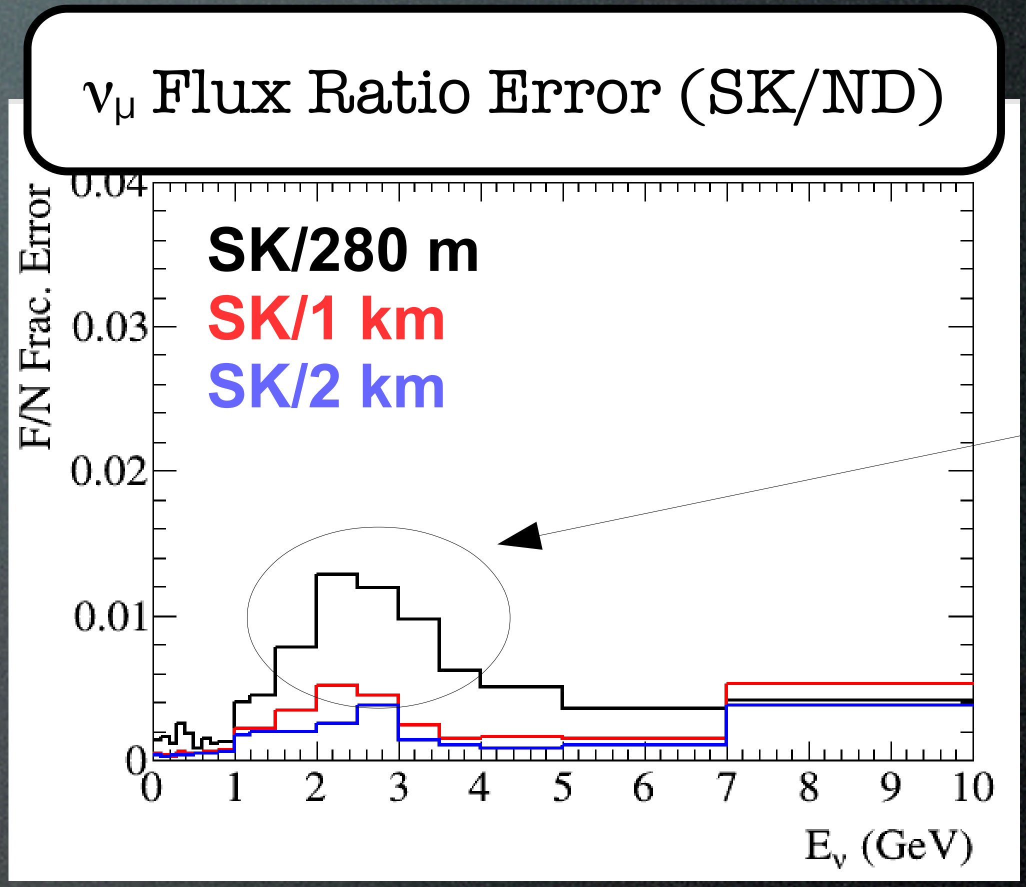






Detector Location: Energy Spectrum Ratio



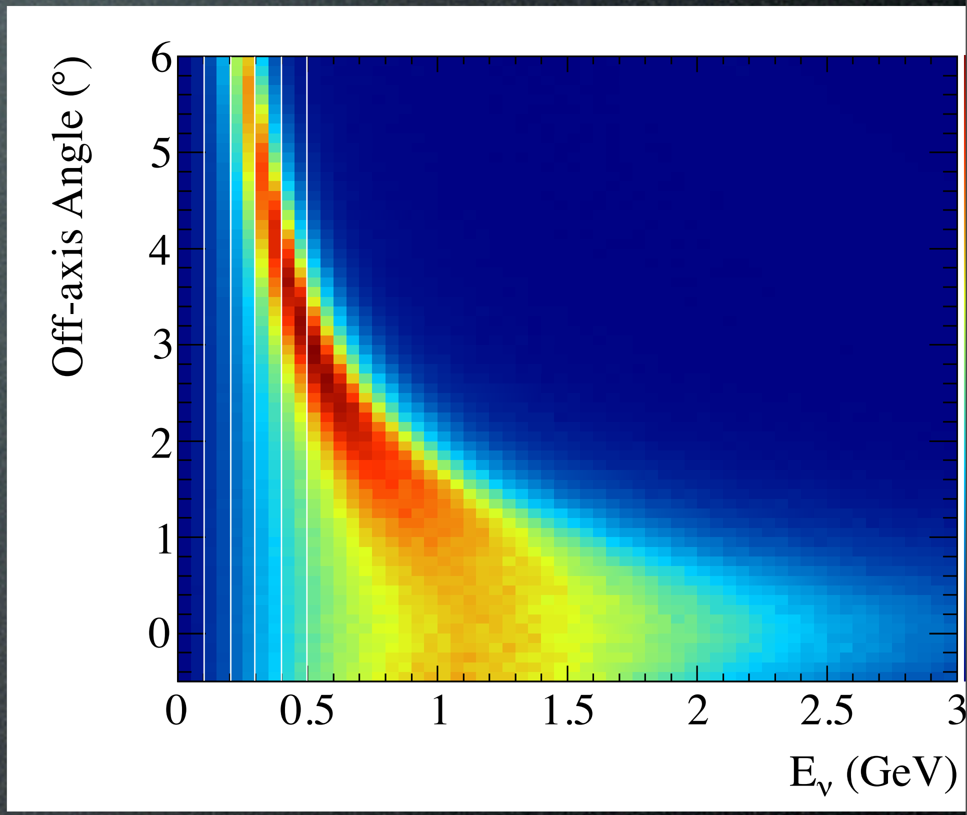


- At 280 m, the flux shape has 20-30% differences below 1 GeV
  - Uncertainty in the ratio is noticeably larger, but mostly above 1 GeV
- The difference between 1km and 2km is small in both shape and shape uncertainty

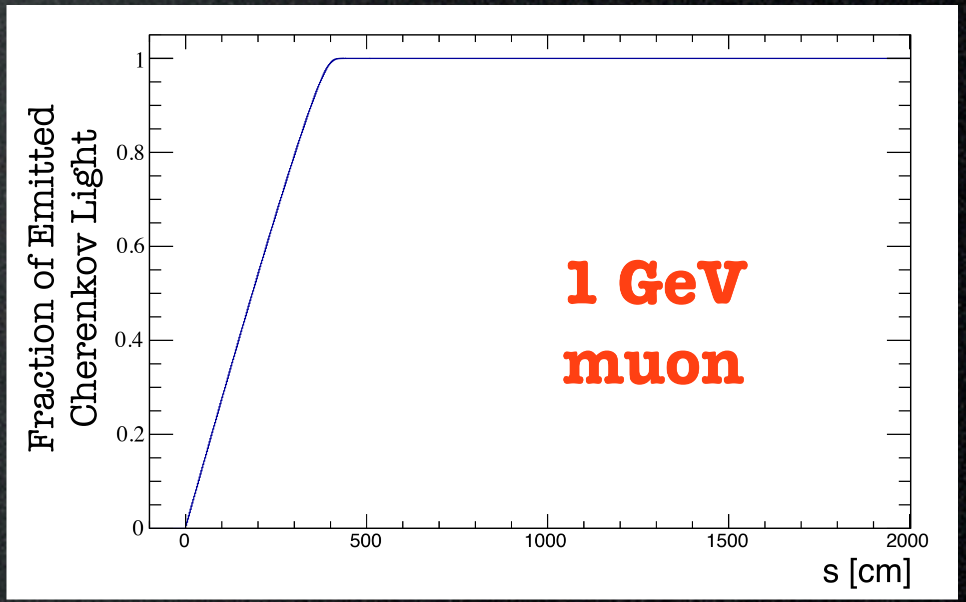
Other Design Considerations

- **Civil construction is expensive!**
  - Smaller hole = More affordable
- **Off-axis angle range (i.e. E_ν range)**
  - On-axis flux peaks at 1.2 GeV
  - 4° (6°) off-axis peaks at ~380 (~260) MeV
  - Beam points 3.63° below horizon, so get ~4° for free
- **Distance to target**
  - At 1 (1.2) km , need 54 (65) m deep pit to span 1°-4°
  - Event pileup must be manageable (see later slides)
- **Tank diameter**
  - Determines maximum muon contained
    - 4 m (+ FV cut) for 1 GeV/c muon
  - PID degrades near the wall
    - Important for selecting e-like events
  - Larger = more stats, but also more pileup
  - Larger = more PMTs = more expensive
  - How much outer detector is necessary?

Off-axis Fluxes

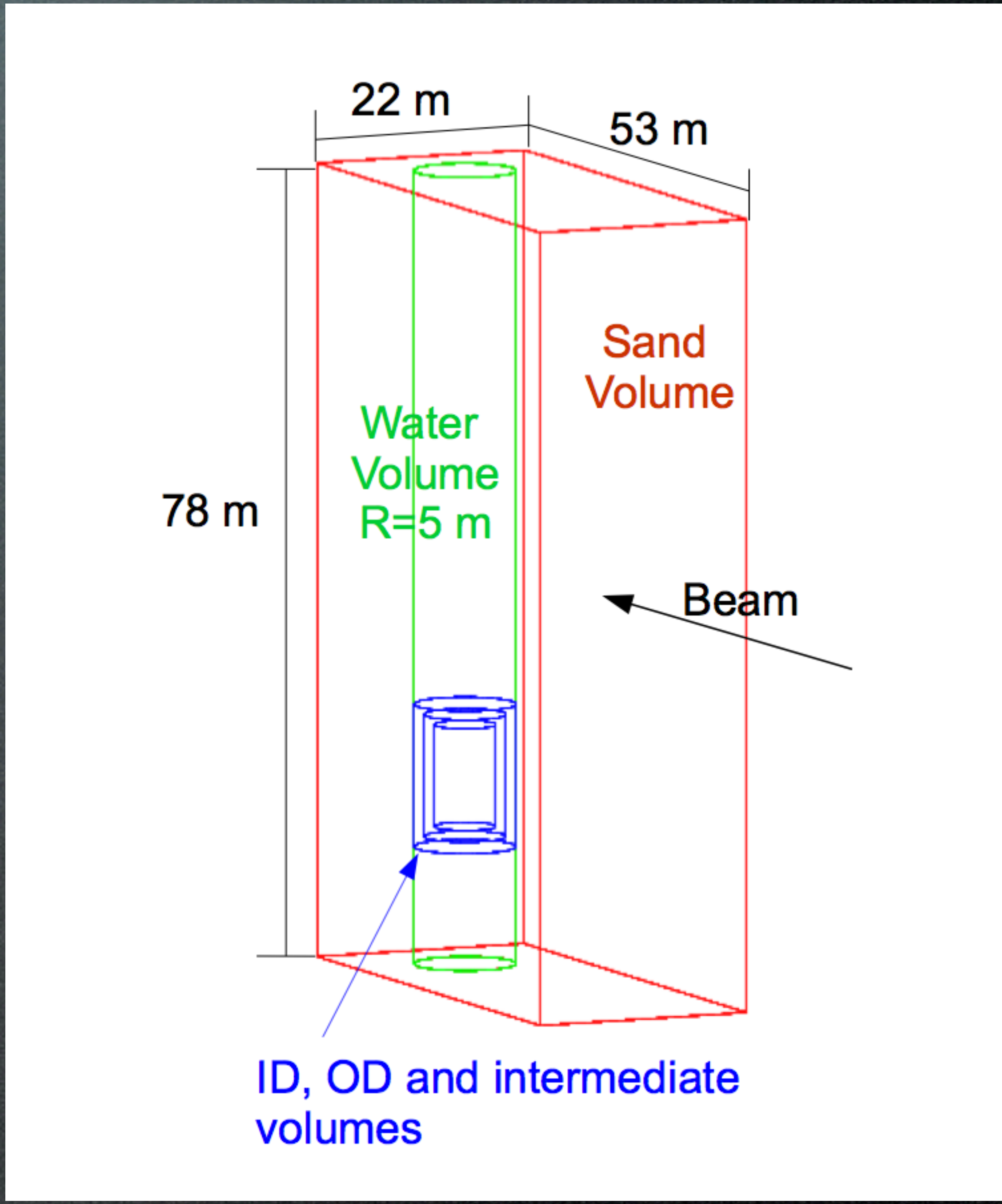


Muon Range



Event Pileup

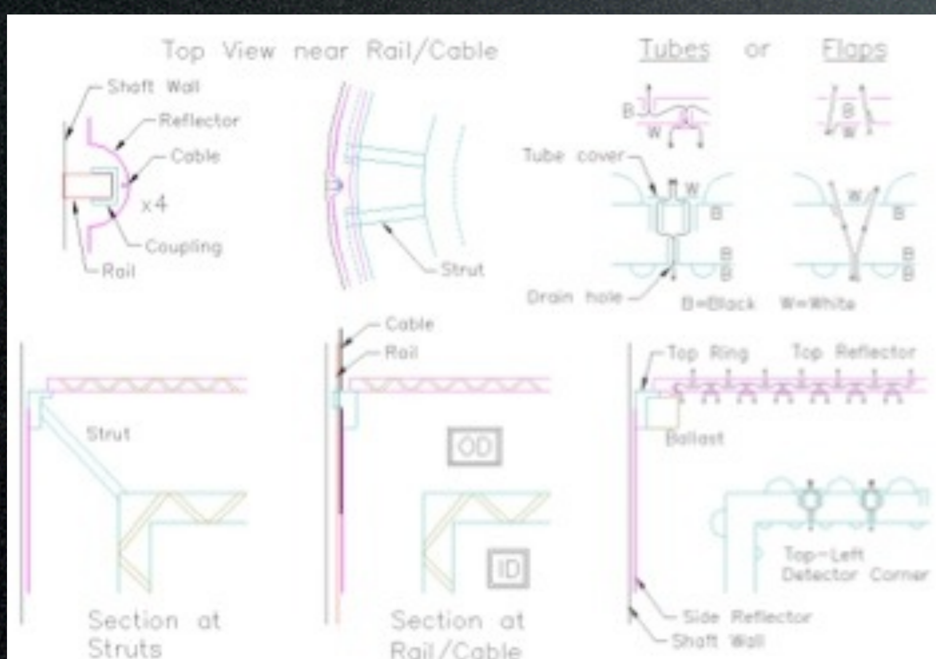
- Full GEANT4 simulation of water and surrounding sand
    - Using T2K flux and neut cross section model
- 8 beam bunches per spill, separated by 670 ns with a width of 27 ns (FWHM)
- **41% chance of in-bunch OD activity during an ID-contained event**
    - Want to avoid vetoing only on OD light (i.e. using scintillator panels)
- **17% of bunches have ID activity from more than 1 interaction**
    - 10% of these have no OD activity
    - Need careful reconstruction studies
        - (but multi-ring reconstruction at Super-K works very well)



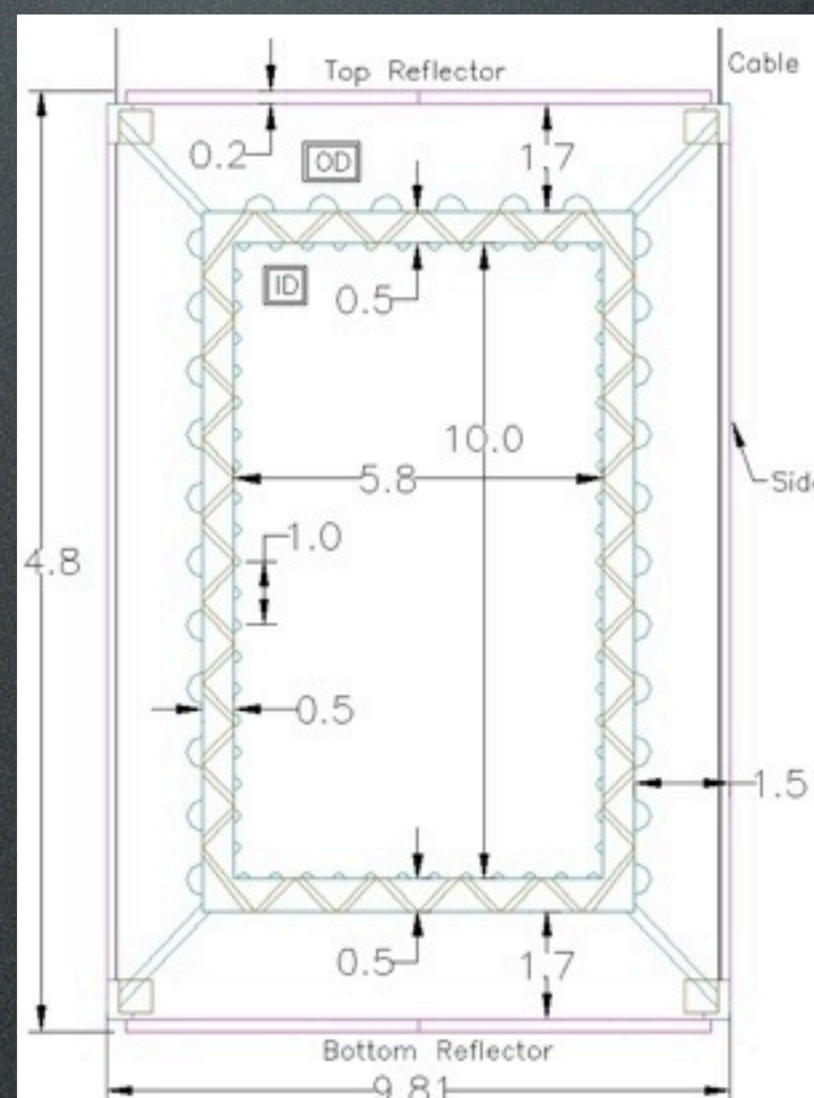
Pileup Rates at 1 km Look Acceptable!

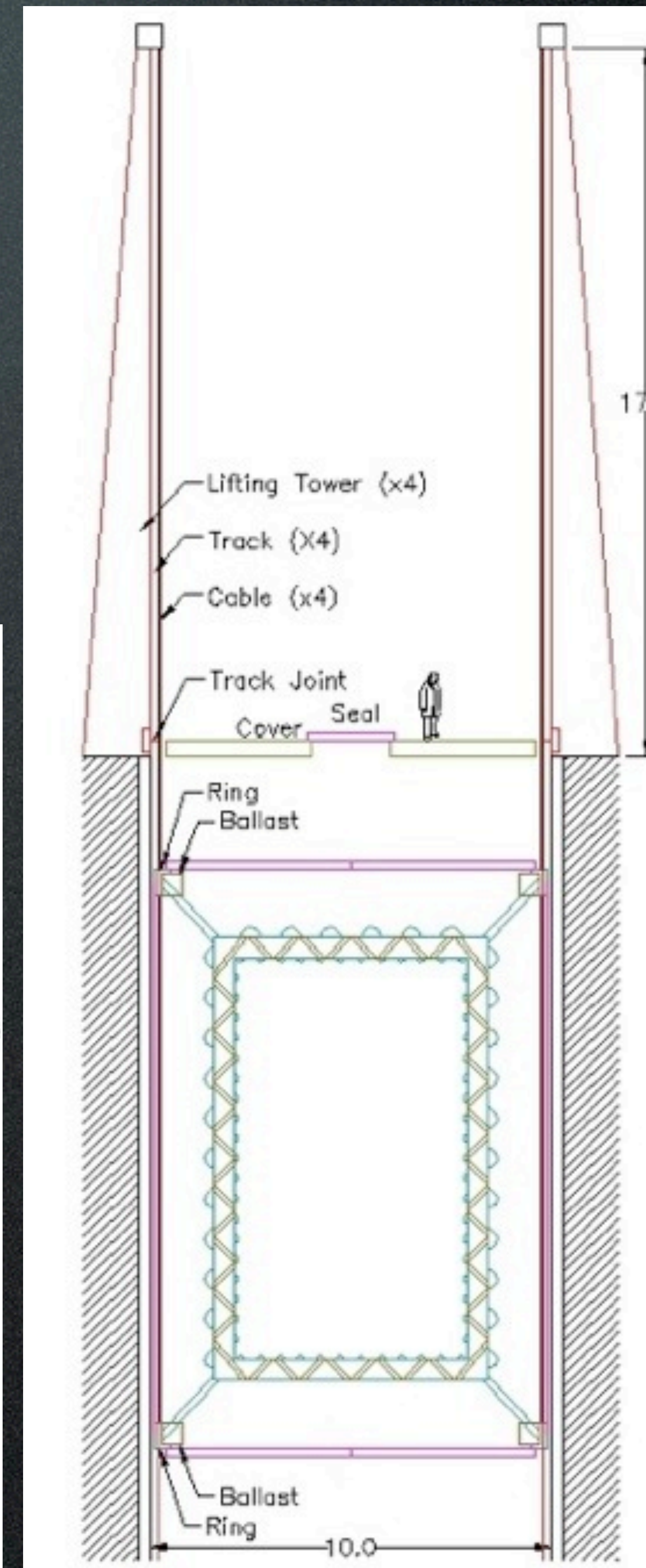
Detector Frame

- Initial proposal for ID/OD frame and lifting mechanism has been produced
- Careful consideration given to water flow rate while in motion
- 4 towers allow the entire detector to be lifted out of the water tank for maintenance



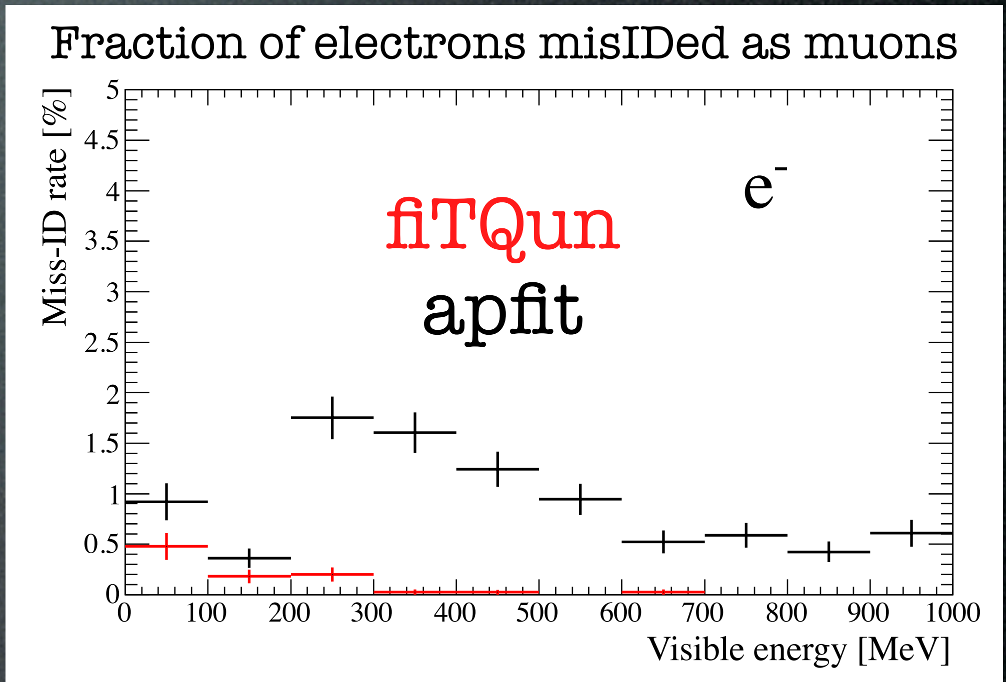
Top View

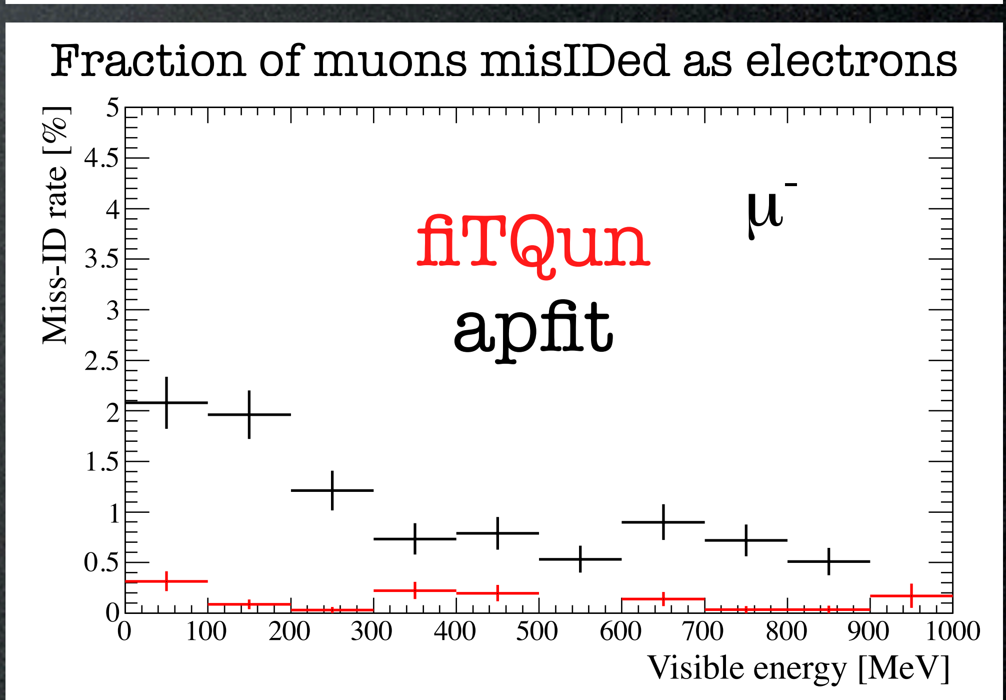




Physics Capabilities

- Direct measurement of the relationship between lepton kinematics and neutrino energy
    - No longer rely solely on models
- 4π detector (like Super-K)
- Target material is water (like Super-K)
    - Can directly measure NC backgrounds
- Very good e/μ separation
- Can make a precise measurement of beam ν_e
    - π^0 background is well separated
    - Can also constrain ν_e cross sections





T2K Uncertainties

ND280 Analysis	ND280 Data	SK Selection	$\sin^2 2\theta_{13}=0.1$	$\sin^2 2\theta_{13}=0.0$
No Constraint	--	Old	22.6%	18.3%
No Constraint	--	New	26.9%	22.2%
2012 method*	Runs 1-2	Old	5.7%	8.7%
2012 method**	Runs 1-3	Old	5.0%	8.5%
2012 method	Runs 1-3	New	4.9%	6.5%
2012 method***	Runs 1-3	New	4.7%	6.1%
2013 method	Runs 1-3	New	3.5%	5.2%
2013 method	Runs 1-4	New	3.0%	4.9%

Factor 2.4 more ND280 POT

Improved SK π^0 rejection

New ND280 reconstruction, selection, binning

Factor 2.2 more ND280 POT

*Results presented at Neutrino 2012 conference

**Published results, arXiv:1304.0841v2

***Update to NEUT tuning with MiniBooNE data

These are very nice constraints!
(if the current parametrization is to be believed)